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ORIGINAL PAPER

Sustainable global energy supply based on lignocellulosic biomass from afforestation of degraded areas

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Abstract An important aspect of present global energy scenarios is the assumption that the amount of biomass that can be grown on the available area is so limited that a scenario based on biomass as the major source of energy should be unrealistic. We have been investigating the question whether a Biomass Scenario may be realistic. We found that the global energy demand projected by the International Energy Agency in the Reference Scenario for the year 2030 could be provided sustainably and economically primarily from lignocellulosic biomass grown on areas which have been degraded by human activities in historical times. Moreover, other renewable energies will contribute to the energy mix. There would be no competition with increasing food demand for existing arable land. Afforestation of degraded areas and investment for energy and fuel usage of the biomass are not more expensive than investment in energy infrastructure necessary up to 2030 assumed in the fossil energy based Reference Scenario, probably much cheaper considering the additional advantages such as stopping the increase of and even slowly reducing the CO_2 content of the atmosphere, soil, and water conservation and desertification control. Most importantly, investment for a Biomass Scenario would be actually sustainable, in contrast to investment in energy-supply infrastructure of the Reference Scenario. Methods of afforestation of degraded areas, cultivation, and energetic usage of lignocellulosic biomass are available but have to be further improved. Afforestation can be started immediately, has an impact in some few years, and may be realized in some decades.

Keywords Afforestation · Bioenergy · Biofuel · Biomass · Energy scenario

Introduction

Presently, about 87% of the global energy mix comes from depleting fuels and, with the exception of the nuclear energy (6%), all are carbon-rich fossil fuels such as oil (35%), natural gas (21%), and coal (25%; International Energy Agency (IEA) 2006a). The economically recoverable proven reserves of oil, natural gas, and coal represent at the end of 2007 about 41.6, 60.3, and 133 years, respectively, of supply at the current rate of consumption (BP 2008). Thus, a simple calculation shows that these proven reserves will be completely exhausted after 75 years at the current rate of consumption of fossil energy (see S1 for details) and most likely earlier considering the increasing worldwide energy demand. As a consequence, the conventional oil production[1] could peak within 20 years

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[1] The unconventional oil production is developing. The Department of the Interior's Bureau of Land Management of the USA published proposed regulations to establish a commercial oil shale program that could result in the addition of up to 800 billion barrels of recoverable oil from lands in the western USA (http://www.doi.gov/news/08_News_Releases/080722.html).

(National Research Council 2006) or earlier (Kerr 2007), followed by natural gas and coal. Growing fossil fuel use is linked with increasing greenhouse gas emissions enhancing the risk of global warming (IPCC 2007) and ocean acidification (Orr et al. 2005). Recently, the economics of climate change was discussed (Stern 2007). Capture and storage of carbon dioxide was proposed (National Research Council 2003; IPCC 2005). Alternatives to fossil fuel use have to be developed and were suggested (German Advisory Council on Global Change 2003; Olah et al. 2006; Shinnar and Citro 2006; Agrawal et al. 2007). A remarkable aspect of all these alternatives as well as of governmental and traditional energy policies is the assumption that the amount of biomass that can be grown on the available area is so limited that a scenario based on biomass as the major source of energy production should be unrealistic (IEA 2004). It is stated correctly that biomass as an energy source has many advantages because the use of biomass is essentially carbon neutral and because it provides a convenient way of storing energy in contrast to other renewable energies. However, a large part of the world's agricultural land would have to be devoted to energy crops if they were to supply a substantial amount of our energy needs. Recently, a hybrid hydrogen–carbon process for the production of liquid hydrocarbon fuels was proposed wherein biomass is the carbon source and hydrogen is supplied from carbon-free energy such as solar, nuclear, wind, etc. The advantage of this process would be that the land area needed to grow the biomass is <40% of that needed by other routes that solely use biomass to support the entire transportation sector (Agrawal et al. 2007; Dietenberger and Anderson 2007). Taken together, it is stated, i.e., by Olah et al. (2006): "Biomass can provide a significant but nevertheless limited amount of energy that is inadequate to sustain our modern society's needs". In contrast, it was claimed that the key factor for bioenergy from specialized bioenergy crops would be the type of agricultural management system applied to produce food. If a type of agricultural management would be applied similar to the best available technology in the industrialised regions, the world would be capable of producing the demand for food projected for 2050 using only a fraction of the present agricultural land. The potential to increase global average crop yields ranges from a factor 2.9 to 3.6. In total, between 0.7 and 3.6 Gha agricultural land could be made available for bioenergy production in 2050 (Smeets et al. 2004, 2006; Hoogwijk et al. 2005). Furthermore, it was suggested to cultivate sugarcane on 143 Mha of unexploited land in tropical countries, mainly in Latin America and Africa, to produce 3,916 million tonnes oil equivalents per year (Mtoe/year) of primary energy and 2,144 Mtoe/year of final energy in the form of ethanol as liquid fuel (Moreira 2006).

We want to discuss here as a thought experiment whether the global energy demand projected by the IEA in the Reference Scenario for the year 2030 (IEA 2006a) may be provided sustainably and economically predominantly from biomass grown on areas which have been degraded and wasted in historical times by human activities in all continents. We are fully aware that in addition to biomass, other available renewable energies from the wind, tides, photovoltaics, and other options will contribute to a future sustainable energy scenario and use in our Biomass Scenario the contribution of these renewable energies as estimated by IEA in the Reference Scenario (IEA 2006a). Moreover, energy conservation and a more efficient usage of primary energy have to be a most important part of the solution.

Results

Global primary energy supply and consumption and CO_2 emissions

The current global primary energy supply amounted to 11,204 Mtoe in 2004. The total final energy consumption was about 7,639 Mtoe. About 16% was used as electrical energy, 26% as transportation fuel, and 9% as nonenergy use and the difference of about 49% mostly as thermal energy. About 32% of the primary energy supply was used for the production of the final usable energy, mostly for power generation. This fact is most remarkable. Of primary energy, 4,133 Mtoe had to be used to produce 1,236 Mtoe (29.9%) of electrical energy and 255 Mtoe (5.8%) of useful heat (IEA 2006a).

Following the current unsustainable path through to 2030, the IEA projects in the Reference Scenario—that is "business as usual"—a linear increase of the global primary energy supply to 14,071 Mtoe in 2015 and to 17,095 Mtoe in 2030, by an average annual rate of 1.6% (IEA 2006a). Fossil energy will remain dominant in this scenario. Massive investments in energy-supply infrastructure of just over $20 trillion from 2005–2030 are projected, remarkably >50% in the developing countries and predominantly in power supply (Table 1).

The consequence of the usage of fossil feedstocks is the emission of CO_2, i.e., 26,077 Mt in 2004. In 2015 and in 2030, a global emission of 33,333 and 40,420 Mt, respectively, is expected in the Reference Scenario. Additional investments of about $400–500 billion would arise for carbon sequestration (IEA 2006a). It may be mentioned that about 14 Mha of land—about 1% of world's arable land—are presently used for the production of biofuels rising in 2030 to over 2.5% in the Reference Scenario competing with increasing food demand for existing arable land.

Table 1 Investment in billion $ in energy-supply infrastructure in the Reference Scenario, 2005–2030 (IEA 2006a)

Country groupings[a]	Coal	Oil	Gas	Σ^b	Power	Total
OECD Countries	156	1,149	1,744	3,049	4,240	7,289
Transition countries	33	639	589	1,261	590	1,850
Developing countries	330	2,223	1,516	4,069	6,446	10,515
Interregional transport	45	256	76	376	-	376
World	563	4,266	3,925	8,754	11,276	20,192

[a] See S2 for details

[b] Σ coal, oil, and gas

Lignocellulosic biomass for global primary energy supply

The average energy content of oven dry wood as the most important lignocellulosic biomass is 0.48 toe/t (IPCC 2001). However, it must be kept in mind that biomass must be transformed in a form suited to technical needs. This transformation will need more energy than the transformation of fossil oil and other fossil fuels (Table 2).

The problems nowadays arising by the fact that the regions of the production of fossil fuels such as oil and the regions of consumption of energy do not coincide will be clearly reduced, because, in principle, biomass for energy use can be cultivated in all countries and each country should be able to produce an important fraction of its primary energy supply. Biomass cannot be transported economically over long distances. Concentration of the energy content of biomass will be necessary. For example, liquid, stable bioslurry can be produced by fast pyrolysis of biomass having approximately 60–65% of the energy content of petroleum. About 10% of the biomass energy content is consumed for this process. The slurry could be shipped similar as petroleum. The investment for a 45,000 toe/year bioslurry facility converting about 100,000 t/year of lignocellulosic biomass is estimated to be about $15 million (Henrich and Dinjus 2004; Dahmen et al. 2007). Overall, we assume that the energy costs of the transportation of biomass and bioslurry will not be higher than the respective fossil fuel costs because of the much shorter distances (Table 2).

Biomass can be used to produce electricity and thermal energy by combined heat and power generation (Bridgwater 1999). Investments are not higher than in coal power stations, however, much less than in nuclear power stations. Additional investments of about $400–500 billion arising for carbon sequestration (IEA 2006a) can be saved as well as investments for nuclear waste treatment and deposition. Because of the transport problem mentioned, it may be advantageous to use bioslurry instead of biomass directly. This would also help to avoid some environmental disadvantages of directly burning biomass (German Advisory Council on Global Change 2003). However, it should be kept in mind that the present technology of production of electricity is not at all efficient. Technological development has the potential to increase the present world average power station efficiency from 30% to more than 60% in the longer term, although capital costs will be significantly higher (IPPC 2001). It is an important challenge to develop new technologies to be able to convert the chemical energy stored in biomass, and in fossil fuels as well, to electrical energy much more efficiently, avoiding the transformation to thermal energy. For example, the Direct Methanol Fuel Cell has a theoretical efficiency close to 97%, although presently still performs well below their theoretical Nernstian potential (Olah et al. 2006).

There are various methods available, however, not fully developed, for the production of transportation fuels from lignocellulosic biomass (Huber et al. 2006; Faaji 2006). It can be assumed that a mix of the most efficient methods, possibly varying regionally, will be implemented eventually. Furthermore, it may be regionally more advantageous to produce bioethanol from sugar cane (Moreira 2006) or biodiesel from oil crops (Johnston and Holloway 2007) or both as biofuel. However, it has been shown by life cycle accounting for the USA that transportation biofuels such as synfuel hydrocarbons or cellulosic ethanol, if produced from low-input biomass grown on agriculturally marginal land or from waste biomass, could provide much greater supplies and environmental benefits than food-based biofuels (Hill et al. 2008). Thus, for our global overall estimations, we used exemplarily the conversion of lignocellulosic biomass via bioslurry (see above) to synthesis gas followed by Fischer–Tropsch synthesis to give a “biomass to liquid” (BtL) biofuel and chemicals, a process being currently in development in Germany (Fachagentur Nachwachsende Rohstoffe 2004; Fachagentur Nachwachsende Rohstoffe 2005; Dahmen et al. 2007). First production plants are expected to be realized in 2010/2011 (Plass and Reimelt 2007). The conversion of the bioslurry is performed in a high temperature process with oxygen. Approximately 75% of the energy content of the biomass can be obtained as clean synthesis gas. Of biomass, 10 toe would yield in Fischer–Tropsch synthesis about 5 toe of synthesis products, about 4 toe of BtL, and in addition, 1 toe of valuable chemicals. As by-products, heat and electricity are generated, by means of which the energy consumption of the

Table 2 Global primary energy supply and global final energy consumptions assumed in 2030. Biomass Scenario compared with Reference Scenario of IEA (2006a)

	Global energy demand Mtoe (%)		
	Reference Scenario[e]	Biomass Scenario—% usage of bioslurry (right column)	
Total primary energy supply	**17,095 (100)**	**20,600 (100)**	
Coal	4,441 (26)	–	
Oil	5,575 (33)	–	
Gas	1,680 (23)	–	
Nuclear	861 (5)	–	
Hydro	408 (2)	408[e] (2)	
Biomass and waste	1,645 (10)	1,645[e] (8)	
Other renewables	296 (2)	296[e] (1)	
Lignocellulosic biomass (LCB)[a]	–	18,300 (89)	
Bioslurry from LCB	**–**	**16,450[f]**	**100**
Power generation and heat plants	**6,926 (100)**	**6,926 (100)**	
Coal	3,232 (47)	–	
Oil	241 (3)	–	
Gas	1,683 (24)	–	
Nuclear	861 (12)	–	
Hydro	408 (6)	408[e] (5.9)	
Biomass and waste	265 (4)	265[e] (3.8)	
Other renewables	236 (3)	236[e] (3.4)	
Bioslurry	–	6,017 (86.8)	33.4
Bioslurry to fuels and chemicals[b]		6,490	36
Other transformations, own use and losses[c]	1,583 (100)	1,583[e] (100)	8.8
Of which electricity	486 (31)	486[e] (31)	
Total final consumptions	**11,664 (100)**	**11,664[e] (100)**	
Coal	923 (8)	–	
Oil	4,786[g] (41)	–	
Gas	1,839 (16)	–	
Electricity	2,416 (21)	2,416[e] (21)	
Heat	324 (3)	324[e] (3)	
Biomass and waste	1,317 (11)	1,317[e] (11)	
Other renewables	60 (1)	60[e] (1)	
Oil/char-slurry[d]	–	3,943 (33)	21.8
Fuel for transport	–	2,884[b] (25)	
Chemical feedstock	–	720[b] (6)	

[a] Lignocellulosic biomass used for the production of bioslurry

[b] The transformation of LCB via bioslurry has an energetic yield based on LCB of 40% of fuel and in addition of 10% of chemical feedstock (Henrich and Dinjus 2004; Dahmen et al. 2007)

[c] See S8 for explanation

[d] Usage in industry, residential, services, agriculture, and nonenergy use

[e] Taken from IEA (2006a, b)

[f] Energetic yield of bioslurry about 90% (Henrich and Dinjus 2004)

[g] Including 2,884 Mtoe for transport

process can be covered completely. The investment for a 1-Mt/year BtL unit has been estimated to \$500 million. The slurry needed will be produced in a decentralized manner in 64 pyrolysis units each producing 45,000 toe per year (Henrich and Dinjus 2004; Dahmen et al. 2007). The global energy demand and consumption expected in 2030 by the Reference Scenario (IEA 2006a) is compared in Table 2 exemplarily with a Biomass Scenario based on the production of bioslurry from lignocellulosic biomass. The total final energy consumption of 11,664 Mtoe in 2030 will be produced from 18,300 Mtoe of lignocellulosic biomass via 16,450 Mtoe of bioslurry and additionally 2,350 Mtoe of hydroenergy, traditional biomass—including bioethanol and biodiesel—and waste and all other renewables as assumed in the Reference Scenario. The slurry will be used comparably to oil for power and heat generation (33.4%), fuel and chemical feedstock production (36.0%), and other energy needs in industry, residential, services, agriculture as well as nonenergy use (21.8%). Energy for transport, own use, and losses (8.8%) were assumed to be the same as in the Reference Scenario. It seems to be remarkable that the production of biofuels needs a higher percentage of primary energy supply than in the Reference Scenario from fossil feedstock. Improved methods of the chemical transformation of biomass to fuels have to be developed and implemented (Huber et al. 2006; Fernando et al. 2006; Faaji 2006). It was suggested to produce methanol from synthesis gas and to use methanol as fuel and as liquid energy storage (Olah et al. 2006). The production of methanol from synthesis gas is technically well developed. The efficiency of transformation is significantly higher (>20%) than the transformation to hydrocarbons in the Fischer–Tropsch process (Fiedler et al. 2000). Of bioslurry, 10 toe would yield about 7.0 toe of methanol and the production of 3,600 Mtoe of methanol as fuel and chemical feedstock consumed in 2030 would necessitate 5,140 Mtoe of bioslurry instead of 6,480 Mtoe. Thus, the production of methanol exhibits obviously advantages in comparison to Fischer–Tropsch synthesis of hydrocarbons. Because of the fact that some problems would arise with methanol as fuel and that the presently available Internal Combustion Engines would have to be modified to methanol-specific engines (Olah et al. 2006), we performed our estimations exemplarily using the Fischer–Tropsch data keeping in mind that methanol would yield higher energy efficiency.

One could also think to follow the suggestion by Agrawal et al. (2007) to supply hydrogen from carbon-free energy and solely <40% of biomass would be needed to support the entire transportation sector. However, the problem has not been solved that the technology is not available to produce the hydrogen from carbon-free energy.

Lignocellulosic biomass cultivation

Fast growing tree species in moderate latitudes produce annually 15 and up to 20 t/ha of wood and in tropical dry forests even up to >30 t/ha (see S3 for more examples). Remarkably, these values have also been established on degraded lands, i.e., *Albizia lebbek* gave 20 t/ha·year and *Dendrocalamus strictus* 32.0 t/ha·year of biomass, on a mine spoil in a dry tropical region of India (Singh and Singh 2006). The above ground biomass production of *Populus deltoides* stands in a semiarid area contiguous to the Thar Desert in India varied from 4 to 10 and 20 t/ha·year, depending upon the tree density of 208, 531, and 2,250 trees per ha, respectively (Puri et al. 1994). Modern methods of plant breeding may be able to improve these yields considerably. The IPCC study considered an average productivity of forests of 15 t/ha·year of oven dry biomass having a primary energy content of 0.48 toe (IPCC 2001; see also Moreira 2006). We use this value for our calculations; however, we anticipate that with growing practice and experience, larger crops of lignocellulosic biomass will be yielded. An area of about 1.56 Gha would have been necessary to provide the global primary energy supply of 11,204 Mtoe in 2004, 1.95 Gha would be needed for 14,071 Mtoe in 2015, and actually, 2.54 Gha, about one fifth of the total global land area, to produce the primary energy supply needed for energy consumption in 2030 estimated in the Reference Scenario (Table 2).

Areas available for biomass production

Arable areas are required to produce food for the increasing global population of up to nine billion in 2050 (Bongaarts and Bulatao 2000) and are not or only most limited available (IPCC 2001; see also Moreira 2006; see, however, the discussion by Smeets et al. 2004 and by Hoogwijk et al. 2005). Pastures, especially poor pastures, may possibly be used for afforestation depending on the conditions in the respective country and considering the fact that a substitute fodder has to be supplied. The production of lignocellulosic biomass and fodder for ruminants can be combined by, i.e., using white rot fungi. A simple method allows the growth of fungi at a commercial scale under the conditions of a remote farm in developing countries, i.e., in Africa making wood digestible for ruminants as has been demonstrated by a recent European Union (EU) project (Hüttermann et al. 2000).

The existing forests may be used only partially for energy supply because of economical, various ecological, and social reasons (FAO 2005). That applies especially to primary forests and forest areas designated for conservation of biodiversity.

The IPCC study estimated that 1.28 Gha of land should be available for energy biomass production giving a primary energy potential of 9,216 Mtoe (IPCC 2001), about 82% of the primary energy supply of the year 2004. Moreira (2006) estimated by comparison of actual and potential available arable land for rainfed agriculture an area of about 2.38 Gha, of which 1.99 are in tropical and 0.38 in temperate regions being available for biomass production. Mankind has been degrading in historical times some billion hectares of areas originally forested and covered with vegetation, respectively (Williams 2003; Lal

2004; UNEP 2002). The Terrastat database (FAO 2003) gives a global area of 0.8 Gha of very severe and of 2.7 Gha of severe human-induced degradation (FAO 2000a, b). This degraded area of 3.5 Gha amounts to 39.4% of the sum of agricultural—arable area and pastures—and forest area (see S6). Globally, the area prone to desertification is estimated to 6.1 Gha being 68.8% of the agricultural and forest area (FAO 2000a, b).

For a possible use of these lands, one fact is very important: Most of the rain which had fallen when the vegetation was still intact will continue to fall, regardless of the state of the land and the lacking water storage capacity (see S4 for details). Thus, provided plants are available which are able to flourish on such soils or techniques which enable a revegetation, most of these lands are a potential source for energy plantations. The afforestation of such degraded lands will have one very important consequence: It will eventually restore the soil organic matter in the soil (see S5 for some examples). Thus, the water storage capacity of these lands will increase considerably and eventually reach the value before the deforestation took place (Querejeta et al. 2001; Chamran et al. 2002; Hajnos et al. 2003).

The importance of the restoration of the soil organic matter for the fertility of soils cannot be underestimated (Lal 2006). Therefore, it may be advisable not to plant the trees in huge plantations but follow agroforestry models with landscape mosaics, where the adjacents sites will profit from the benign development of the forests with regard to water storage and soil organic matter (Lal 2004).

A high percentage of these degraded areas should be available and suited for afforestation, albeit still in use for crops or pasture at low productivity. To combat the ongoing desertification (FAO 2000a, b; UN 1992) and to improve the fertility of soils (see above), it would be in the objective interest of the respective countries, of the local population, and in the general interest of mankind to afforest these degraded areas and to use the biomass continuously for the production of the necessary energy, fuel, materials, and chemicals of the respective country and, if possible, for export.

Two important examples may be mentioned. The Indian government declared that degraded area of about 153 Mha should be developed to tackle continuous degradation of land, decreasing vegetative cover, soil erosion, and depleting water resources (Government of India, Ministry of Environment and Forests 2006).

China is one of the countries in the world suffering from severe desertification over a vast area. The area prone to desertification is 331.7 Mha accounting for 34.6% of the total territory. By the end of 2004, the area of desertification was 263.6 Mha, taking up 27.4% of the total territory and 79.4% of the area prone to desertification which is higher than the world's average of 69% (China National Committee for the Implementation of the UNCCD 2006; Ma 2004). Remarkably, the tendency for desertification and sandification to expand has started to be restrained by the program to combat desertification. The process of desertification has been reversed from an average annual expansion of 1.04 Mha in late twentieth century to an average annual contraction of 0.76 Mha during 1999–2004 (China National Committee for the Implementation of the UNCCD 2006).

Afforestation of degraded areas

Afforestation of degraded areas is the greatest challenge on the way to a sustainable development. Without afforestation, the desertification will further progress transforming more and more of the areas prone to desertification into new deserts. Afforestation methods and techniques are available, however, have to be improved and developed. Minimal amounts of fertilizers, herbicides, and insecticides should be used and the water needs have to be most limited (Lal 2004; Olah et al. 2006; Shinnar and Citro 2006). Trees have to be selected which are most appropriate for the respective region. The harvest should occur after the maximum growth rate of the respective trees. For example, poplars, aspens, and willows can be cultivated in short rotation forestry with a rotation period of fewer than 10–12 years (Weih 2004). After the harvest, the trees should be able to sprout from the stumps. Some examples of high productivity trees on degraded land were mentioned above (see S3 for more examples). Clearly, the optimal productivity will not be yielded immediately but will improve with restoration of the soil organic matter (Lal 2004).

One of us has found out that in many cases stands, in which trees fail to grow, can be afforested with the help of hydrogels, i.e., superabsorbant polymers (Hüttermann et al. 1999). Superabsorbant polymers are, i.e., cross-linked polyacrylates of very high molecular weights binding water up to 400 times their weight (Frank 2007). Greenhouse experiments have shown that a mixing of desert sand with 0.3–0.4% of hydrogel can prolong the survival of trees under water stress up to 300% (Hüttermann et al. 1999). In addition to the protection against water stress, the hydrogel can help the tree to survive also other types of stress factors such as salt, soil acidity, and heavy metals (Hüttermann et al. 1997). The amendment of the soil in the plant hole with 40 g hydrogel made the difference between a successful plantation and its failure. These results were confirmed in the meantime for various tree species in parts of the hot–dry valleys in China and the method is being applied in China to perform afforestation (Ma and Nelles-Schwelm 2004). It can be expected that the hydrogel will be incorporated into the humus cycle and transformed to humus and eventually to carbon dioxide again (Eichhorn and Hüttermann 1994).

Costs of afforestation and necessary investment

The costs of afforestation will be variable depending on the respective country (see S7 for details). It will be much lower in developing countries than in industrialized countries and vary from approximately \$150 per ha in China (Ma 2004) up to about \$5,000 per ha in Austria (Neumann 2000). In these figures, the cost of land is, as is usually the case with such calculation, not included. The costs which will arise for maintenance are estimated to range from about \$5 (China) to \$50 (Austria) per ha and year. Because of the fact that most degraded areas are situated in developing countries (65%), in contrast to Organization for Economic Cooperation and Development (OECD; 20%) and transition countries (15%), OECD countries especially Japan and the EU will have to import products produced from biomass as today oil, coal, and natural gas to satisfy their energy and fuel needs (Table 3). It has to be studied in more detail which countries may be able to produce completely their biomass needs on their own area, which will become exporters or which will become importers of biomass.

We estimate costs of \$2.927 trillion globally for afforestation of 2.54 Gha of degraded areas necessary to satisfy the global energy demand in 2030 and of \$5.49 trillion investment for pyrolysis units to transform biomass in bioslurry. About 2,884 Mtoe of liquid fuel, i.e., BtL have to be produced for transportation. Having each a capacity of 1 Mtoe/year, 2,884 BtL units will be necessary. The investment for one unit is estimated to be \$0.5 billion (Henrich and Dinjus 2004) giving a global investment of \$1.442 trillion. In summa, \$9.858 trillion are estimated for afforestation, pyrolysis, and BtL production. The Reference Scenario projects for investment in exploration and development as well as refining of oil, gas, and coal \$8.754 trillion, however, not considering CO_2 sequestration and nuclear waste disposal. In the Reference Scenario to be an investment in power generation, transmission, and distribution, \$11.276 trillion (56%) are estimated and \$0.376 trillion (1.8%) in interregional transport (see Table 1). We assume that comparable investment will be necessary also in the Biomass Scenario for power stations using bioslurry and for interregional transport. To sum up, the investment for a sustainable, global biobased economy would be in our conservative estimation \$21.51 trillion including afforestation, about \$1.104 trillion more than the investment estimated up to 2030 in the Reference Scenario (Table 1 and 3). The most important difference to be considered is the fact that the investment necessary in the Reference Scenario will require after 2030 even more increasing investment in exploration and development of the steadily more depleting and more difficultly accessible fossil feedstock (IEA 2008), not to forget the increasing costs for CO_2 sequestration and nuclear waste deposition whereas the investment for a biobased economy would be actually sustainable. The IEA estimated the cost of avoided CO_2 emissions—when fully commercialized—in all countries,

Table 3 Energy demand in 2030 in the Reference Scenario (IEA 2006a), areas and costs of afforestation, investment for the production of bioslurry, and of liquid fuel (BtL) for transportation and chemical feedstock

	OECD	Transition	Developing	World[i]
Primary energy supply Mtoe (%)[a]	6,162 (41.8)	1,349 (9.1)	7,038 (47.7)	14,746 (100)
Primary biomass supply Mtoe (%)[b]	7,650	1,665	8,729	18,300
Area of afforestation Gha[c]	1.06 (0.7)	0.23 (0.25)	1.21 (1.59)	2.54 (2.54)
Costs of afforestation \$ billion[d]	2,100	350	477	2,927
Bioslurry production Mtoe[e]	6,876 (4,540)	1,498 (1,621)	7,856 (10,303)	16,470
Investment for bioslurry \$ billion[f]	2,295 (1,513)	499 (540)	2,618 (3,434)	5,490
Fuel consumption Mtoe[g]	1,571	133	1,180	2,884
Investment fuel production \$ billion[h]	785	66	590	1,441

[a] Primary energy supply of Reference Scenario diminished by the contribution of hydro, biomass, and waste and of other renewables (IEA 2006a)

[b] Primary energy supply of lignocellulosic biomass in Biomass Scenario. The same percentage of OECD, transition, and developing countries as in Reference Scenario was used for simplification

[c] Area of afforestation needed to fulfil the energy demand assuming an average annual growth of wood of 15 t/ha. In brackets: area which should be afforested taking into account available very severe and severe human-induced degraded area (FAO 2000a, b)

[d] Estimated for the areas given in line 3 in brackets using average costs of afforestation per ha: OECD countries—\$3,000, transition countries—\$1,400, developing countries—\$300 (see S7 for details)

[e] Estimated for the areas of afforestation given in line 3 in brackets (see S9 for data used in calculations)

[f] Investment for production of bioslurry given in line 5; investment per production unit equivalent to 45,000 toe/year is estimated to be \$15 million (Henrich and Dinjus 2004)

[g] Consumption of liquid fuel in 2030 (IEA 2006a, b)

[h] Investment for production of fuel from bioslurry (see line 5); investment per 1 Mt/year BtL unit is estimated to be \$0.5 billion (Henrich and Dinjus 2004)

[i] Differences due to international marine bunkers (see S8)

including developing countries to be not more than \$25 per tonne (IEA 2006b). The annually avoided CO_2 emissions of up to 40,420 Mt—generated in the Reference Scenario in 2030—would sum up, when fully commercialized, to \$1 trillion per year, enough to make the afforestation of degraded areas profitable and economically feasible. Moreover, Stern estimated that the social cost of carbon is of the order of \$85 per tonne of CO_2 (Stern 2007), more than \$3.4 trillion in 2030. Interestingly, the OECD countries will have to import about 35% of their energy in the Biomass Scenario and will have to make considerable investments in afforestation and in facilities for processing of the biomass in developing countries which will become exporters of bioenergy and biofuels (Table 3).

CO_2 sequestration

The forests on the afforested area of about 2.54 Gha will have bound permanently approximately 267 Gt of carbon being equivalent to 979 Gt of CO_2 assuming that each year about 1/15 of the area is harvested and this fraction goes back as CO_2 in the carbon cycle. Furthermore, the carbon content of the soil of degraded areas is much lower than the soil of forests. Carbon will be rebound with afforestation as below-ground biomass and humic compounds will be formed thus sequestering carbon from the air sustainably as long as the forest exists. In temperate forests, an average amount of total detritus of 118 t/ha C, in tropical forests of 104 t/ha C was reported (Schlesinger 1977), equivalent to 430 t CO_2/ha and 380 t CO_2/ha, respectively. Lal estimated the cumulative historical C loss of soils at 55 to 78 Gt and the attainable soil sink capacity at 50% to 66% (Lal 2004). Thus, the afforestation of the degraded areas could sequester about 100–190 Gt of CO_2 below-ground. In summa, 1,079–1,169 Gt of CO_2 could be bound permanently being approximately the sum of the energy related CO_2 emissions of 1,214 Gt from 1990 to 2004 (349 Gt) and the expected cumulated emissions from 2005–2030 of 865 Gt in the Reference Scenario (IEA 2006a).

Time window of afforestation

The time window of afforestation is difficult to estimate. Afforestation is a slow process under the present conditions of business as usual. However, under economically feasible conditions, this process would be accelerated importantly. We assume that the required area of 2.54 Gha should be afforested within 50 years giving a global afforestation rate of 50.8 Mha/year. For example, India would have to afforest approximately 160 Mha according to 3.2 Mha/year to fulfil the primary energy supply assumed in 2030. Remarkably, in the framework of the implementation of the UN Convention to Combat Deforestation, India set the target to develop 153 Mha of degraded area and to reforest about 60 Mha from 2002–2022, approximately 3 Mha/year (Government of India, Ministry of Environment and Forests 2006).

Discussion

As pointed out in the introduction, various alternatives to fossil fuel use have been suggested such as the increased usage of nuclear energy (Olah et al. 2006; Agrawal et al. 2007), of concentrated thermal solar energy (Shinnar and Citro 2006), and of solar cells (German Advisory Council on Global Change 2003) and many other suggestions (Holdren 2007). The problem with all these methods and techniques is that eventually mankind may have power stations producing power and various amounts of waste which have to be deposited, possibly reducing the emissions of CO_2. In contrast, exclusively the afforestation of degraded areas and usage of the wood as renewable feedstock has important additional advantages helping to solve problems of the conservation and management of resources for development as tackled in the Rio documents and Agenda 21 (UN 1992). All forests and woodlands, even "productive" forests, have varying degrees of protective roles. These protective functions range from soil and water conservation to sand-dune stabilization, windbreaks, desertification control, and coastal protection (FAO 2005; Lal 2004). In addition, as has been shown by the introduction of agroforestry practices in the tropical zones, if done properly, afforestations will increase the fertility and water status of the adjacent agricultural lands. Since the conversion of the wood will have to be performed in the countryside, where the forests grow, this will certainly slow down, if not revert, the process of urbanization in the developing countries. Furthermore, it can be assumed that the infrastructure which has to be established in the countryside may probably attract other industries there.

The increase of the CO_2 content of the atmosphere can be stopped because, in principle, the complete energy supply in the Biomass Scenario is CO_2 neutral. Most importantly, the CO_2 content may slowly be reduced. In addition, this reduction of CO_2 will affect positively the oceans and reduce ocean acidification (Orr et al. 2005).

The implementation of the United Nations programs to combat desertification and deforestation (UN 1992) has to be greatly intensified. The scenario of afforestation for energy use will be an important step to realize these UN programs without additional costs.

A historical consequence of degradation of forest areas was increasing the global river runoff significantly during the twentieth century (Labat et al. 2004) and producing widespread watershed degradation (UN 2006). Conversely, a consequence of reforestation may be that the global water and especially drinking water resources will be regenerated and stabilized sustainably (Piao et al. 2007). Moreover, reforestation may help to reduce the frequency and severity of flood-related catastrophes (Bradshaw et al. 2007). Furthermore, deforestation resulted in increased sediment loads, with various impacts on downstream and coastline habitats (UN 2006). It can be expected that afforestation will slowly stop this process.

Afforestation of degraded areas is an important contribution to an integrated approach to the planning and management of land resources (UN 1992). In contrast to the present practice and to, i.e., the Alternative Policy Scenario discussed by IEA (IEA 2006a), afforestation will also improve the base of a sustainable supply with food and other necessary goods for the global population (Lal 2004). In addition, high-value jobs will be created in rural areas of developing countries, in contrast to all other scenarios presently discussed.

Conclusion

In conclusion, our thought experiment might give evidence that the global energy demand could be supplied sustainably by afforestation of areas degraded by human activities and to use the biomass continuously for the production of the necessary energy, fuel, materials, and chemicals. In addition, all other renewable energies will contribute to the energy mix. Moreover, we have been demonstrating that this Biomass Scenario would not be more expensive than the Reference Scenario of the IEA, probably much cheaper considering the additional advantages. Clearly, it cannot be realized in 2030 because it has not been started. However, if afforestation to realize the Biomass Scenario would have been started say in 1992 after the Rio conference, we could observe already today an impact which would steadily increase and lignocellulosic biomass would contribute an important percentage to the primary energy supply in 2030.

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Sustainable Global Energy Supply Based on Lignocellulosic Biomass from Afforestation of Degraded Areas.

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Supporting Information

Abbreviations

Energy toe tonne of oil equivalent
Mass Mt million tonnes (1 tonne x 10^6)
Gt gigatonnes (1 tonne x10^9)
Area ha hectare
Mha million hectare
Gha giga-hectare (1 hectare x10^9)
Biomass production t/ha·year tonnes per hectare and year

S1: Proved Reserves of Fossil Fuels and Time of Consumption of the Proved Reserves.

Proved reserves – Generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known deposits under existing economic and operating conditions.

Reserves-to-production (R/P) ratio– If the reserves remaining at the end of the year are divided by the production in that year, the result is the length of time that those remaining reserves would last if production were to continue at that rate (BP 2008).

Proved reserves at end 2007: Oil 41.6, natural gas 60.3, coal 133 years (BP 2008). Present percentage of consumption of fossil feedstock: Oil 43.2%; natural gas 30.9%; coal 25.9% (IEA 2006). After 41.6 years all oil will be – formally – consumed and the 43.2% of oil have to be (formally) substituted by natural gas which will be consumed 7 years later. Now, all the fossil energy will be coal which will be consumed after additional 26 years, Thus, the presently proved reserves of oil, natural gas and coal will be consumed at the current rate of consumption after 74.6 years.

S2 Regional Groupings of Countries (IEA 2006)

OECD Europe

OECD Europe consists of Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

OECD North America

OECD North America consists of the United States of America, Canada and Mexico.

OECD Pacific

OECD Pacific consists of Japan, Korea, Australia and New Zealand.

Transition Economies

The transition economies include: Albania, Armenia, Azerbaijan, Belarus, Bosnia-Herzegovina, Bulgaria, Croatia, Estonia, the Federal Republic of Yugoslavia, the former Yugoslav Republic of Macedonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Romania, Russia, the Slovak Republic, Slovenia, Tajikistan, Turkmenistan, Ukraine and Uzbekistan. For statistical reasons, this region also includes Cyprus, Gibraltar and Malta.

Developing Countries

Developing countries include: China and countries in East Asia, South Asia, Latin America, Africa and the Middle East (see below for countries included in each regional grouping).

China

China refers to the People's Republic of China.

East Asia

East Asia includes: Afghanistan, Bhutan, Brunei, Chinese Taipei, Fiji, French Polynesia, Indonesia, Kiribati, Democratic People’s Republic of Korea, Malaysia, Maldives, Myanmar, New Caledonia, Papua New Guinea, the Philippines, Samoa, Singapore, Solomon Islands, Thailand, Vietnam and Vanuatu.

South Asia

South Asia consists of Bangladesh, India, Nepal, Pakistan and Sri Lanka.

Latin America

Latin America includes: Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, the Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, St. Kitts-Nevis-Anguilla, Saint Lucia, St. Vincent-Grenadines and Suriname, Trinidad and Tobago, Uruguay, and Venezuela.

Africa

Africa comprises Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, the Central African Republic, Chad, Congo, the Democratic Republic of Congo, Côte d’Ivoire, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, the United Republic of Tanzania, Togo, Tunisia, Uganda, Zambia and Zimbabwe.

Middle East

The Middle East is defined as Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, the United Arab Emirates and Yemen. It includes the neutral zone between Saudi Arabia and Iraq.

S3 Some examples of trees showing an annual growth rate of about 20 t/ha and higher.

Species	Country	Biomass t/ha·year	Ref.
Acacia mangium	Bangla-Desh Amazon Region	20 17	(Shah-Newaz and Millat-Mustafa 2006) (Souza et al. 2004)
Albizia lebbek	India, old coal field	20	(Singh and Singh 2006)
Castanopsis kawakamii	China	27	(Yang et al. 2007)
Casuarina equisetifolia	Costa Rica	25	(Parotta 1999)
Dendrocalamus stricta	India, old coal field	24 32	(Shah-Newaz and Millat-Mustafa 2006) (Singh and Singh 2006)
Eucalyptus grandis	Australia South Africa Brazil	34 20 20	(Tiarks and Nambiar 2000)
Leucaena leucocephala	India Puerto Rico	21 18	(Pathak and Gupta 2005) (Parrotta 1999)
Melia azedarach	India	25	(Gopichand 2005)
Populus deltoides	Canada India, Thar desert	20 20	(Heilmann and Gang 1993) (Puri et al. 1994)
Robinia pseudoacacia	India	15-20	(Gopichand 2005)
Salix	Sweden	20	(Christersson 1986)

S4 Degraded Lands

Degraded lands should not be mistaken with the classical deserts. According to the definition of the FAO, degraded lands by human activities are areas which have been subjected either to economic activities: open strip mining, dumping of mine spoils etc. or where a dramatically change of land use has occurred. The FAO definition makes the meaning of land degradation very clear: “Reduction or loss, in arid, semi-arid and dry sub-humid areas, of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, range, pasture, forest and woodlands resulting from land uses or from a process of combination of processes, including processes arising from human activities and habitation patterns, such as: (i) soil erosion caused by wind and/or water; (ii) deterioration of the physical, chemical and biological or economic properties of soil; and (iii) long-term loss of natural vegetation (FAO 2000).

The starting point for such land degradation usually is the deforestation of the land. The first description of such a process is given by the Greek philosopher Plato in his book Critias (Weeber 1990). He describes the fate of the Greek Islands: At the beginning, there was abundance of wood on the mountains, which kept the water and gave it to the fields in the valley, ensuring fertility. Then the woods were cut and erosion took the soils away. The final state is described by him: “there are remaining only the bones of the wasted body, as they may be called, as in the case of small islands, all the richer and softer parts of the soil having fallen away, and the mere skeleton of the land being left.”

The most important consequences of such a change in land-use are the following (Lumley 2002, Jha 2003, van den Top 2004):

- erosion
- lack of organic matter in the soil
- environmental degradation

S5. Belowground Organic Matter Accumulation after Afforestations

Species	Country	belowground organic matter accumulation t/ha·yr	Ref.
Acacia cachetu	India	5	(Jha and Gupta, 2005)
Casuarina equisetifolia	Costa Rica	5	(Parotta, 1999)
Dalbergia sissoo	India	6.2	(Jha and Gupta, 2005)
Dendrocalamus strictus	India,	21	(Singh et al., 2006)
Eucalyptus robusta	Costa Rica	4	(Jha and Gupta, 2005)
Eucalyptus hybrid PFI	Republic du Congo	2.5	(Laclau et al., 2006)
Eucalyptus spec.	India	6.3	(Jha and Gupta, 2005)
Leucaena leucocephala	Costa Rica	4	(Parotta, 1999)
Pinus elliottii	China, Jiangxi Prov.	2,4	(Wang et al., 2004)
Pinus roxburghii	India	3.6	(Jha and Gupta, 2005)
Tectona grandis	India	4.3	(Jha and Gupta, 2005)

S6. Globally Available Land

World	Total Land Area[1,2]	Arable Land[1]	Pasture[1]	Forests[1],[3]	Steeplands >30% [4,5]	Degraded Land[4]	Deserts Hyperar.[4]
Mha	12 912.3	1 536.4	3 387.1	3 950	1 467.2	3500.7 [6]	2 563.7

[1] Data taken from (FAO 2006); [2] Total area excluding area under inland water bodies and ice; [3] Land under natural or planted stands of trees, whether productive or not; [4] Data from (FAO 2003) ; [5] It is assumed that steeplands >30% will not be suited for production of biomass for energy; [6] Sum of “very severe” and “severe” degraded area being part of the areas of column 3-6.

S7 Costs of afforestation and maintenance ($/ha) in different parts of the world.

Country	Afforestation $/ha	Maintenance $/ha·yr	References
Austria	2000 – 5000	8 – 26	Neumann 2000
Canada	1500 – 2000	5 – 10	McKenney et al. 2004, 2006; Yemshanow et al. 2005
China	25 – 150	5	Ma 2004
Ethiopia	115 – 225	8 – 15	Jagger and Pender 2003
India	100 – 650	5	Balooni 2003

S8

Other Transformations, Own Use and Losses

This covers in Table 2 the use of energy by transformation industries and the energy losses in converting primary energy into a form that can be used in the final consuming sectors. It includes energy use and loss by gas works, petroleum refineries, coal and gas transformations and liquefaction. It also includes energy used in coal mines, in oil and gas extraction and in electricity and heat production. Transfers and statistical differences are also included in this category. (IEA 2006) It includes in the Biomass Scenario the energy needed for transport of biomass, whereas the transformation of biomass to bio slurry is not included.

International Marine Bunkers

This covers those quantities delivered to sea-going ships of all flags, including warships. (IEA 2006)

S9

Some basic data used in calculations of Table 2 and 3

1 t of oven-dry lignocellulosic biomass = 0.48 toe.

10 toe of biomass (20.83 t) give 9 toe of bioslurry
yielding in Fischer–Tropsch synthesis 4 toe of BtL, and 1 toe of valuable chemicals.

1 ha gives in average 15 t/year of lignocellulosic biomass.

Investment for a 45,000 toe/year bioslurry facility converting about 100,000 t/year of lignocellulosic biomass: $15 Mio.

Investment for a 1-Mt/year BtL: $500 million

References are given in the main paper.

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