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Renewable energy and food supply: will there be enough land?

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Abstract

The use of renewable energy sources like photovoltaic systems and biomass plantations require land to intercept incoming solar radiation. This implies that the total amount of energy that can be obtained from these sources is limited. Next to this land is also in use for other purposes, of which food production is the most important. The area required for both food and energy supply depends on one hand on the consumption and on the other on the production per m^2. Large differences in both production and consumption are observed globally. In this analysis distinction is made in land use requirements in so-called 'poor' and 'rich' circumstances. It is shown that in poor circumstances there is not enough land to fulfill the needs for food and energy when biomass is used as and energy source. In the rich situation prospects seems to be better, but in that case a large-scale transformation is required of woodlands and forests into intensive energy crop plantations. When PV-systems are used, the land area required for energy is reduced to a large extent. Their large-scale implementation is not possible on the short term due to technical problems. It is concluded that in the near future energy from biomass is the most likely renewable energy source, however, this source cannot fulfill all the energy requirements. For the more distant future energy from PV-systems seems to have the largest potentials, however, implementation requires large changes in present energy infrastructure.

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Abbreviations: EJ = 10^{18} J; GJ = 10^9 J; MJ = 10^6 J; Gha = 10^9 ha; Mg = 0^6 g = 1000 kg

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1. Introduction

The global (fossil) energy use is estimated to be 400 EJ per year [6,7], which is 0.01% of the annual incoming solar radiation (3.5×10^6 EJ). Although the incoming solar radiation is far larger than the total energy use, this energy source is hardly in use in the modern societies. The very limited use of solar radiation as energy source can be explained by the fact that societies do not need just energy but require energy of certain qualities. Societies need energy to play radios, to power machines, to heat houses, etc. The incoming solar radiation does not possess the qualities to fulfill these needs. Another important issue is that modern societies need energy at certain moments. When it is dark to light a lamp and in winter, when it is cold, to heat the house. The incoming solar radiation shows a typical diurnal (day–night) and seasonal (summer–winter) variation that makes it difficult to fulfill the time-dependent energy needs of societies. For being of use in modern societies, incoming solar radiation has to be converted into an energy carrier that fits in the existing energy infrastructure. An example of such a conversion is the use of photovoltaic cells in which solar energy in converted into electricity. This electricity can be stored in a battery and the battery can be used when energy is needed.

Another option is the use of plant material (biomass, wood). In the photosynthetic process incoming solar radiation is converted into structural plant material (wood), at the end of the growing season the crop is harvested and the wood is used as feed stock for electricity plants.

In general, the efficiencies of these converting systems are low, so that large areas are needed to collect the incoming solar radiation. Next to this the price per energy unit delivered is high in comparison with the present low fossil energy prices (in the case of photovoltaic systems prices are over 20 times as high). Which makes the use of this energy source economically not feasible. Further a large number of technical problems exist that curtail implementation of this energy source. An important drawback is the lack of large capacity storage systems for electricity that can adapt the high variable solar radiation flux to the time-dependent needs of societies.

However, the need for renewable energy sources as a method to mitigate the enhanced greenhouse effect, puts incoming solar radiation as energy source for modern societies into the footlights again.

The fact that this energy source does not fit into the present energy infrastructure does not imply that its use in future is unfeasible. History has shown several changes in energy carriers used by societies and consequent changes in the energy infrastructure.

1.1. Historical changes in energy supply systems

Before the industrial revolution the total consumption was low and energy conversion was limited to burning of fuel wood for heating and cooking. Humans, horses, windmills and watermills provided mechanical power. The introduction of the steam engine powered by coal caused a large change in the energy system. It was the first conversion from fossil energy into work. Further since coal can be transported and stored, the work could be done on the site where it was required. This is in contrast to windmills and watermills where the work had to be done on the site where the energy was. This led to a new organisation of the production: the factories. The development of the mobile steam engine had large impacts for the transportation system. At the beginning of the 20th century coal had replaced nearly all traditional energy sources and global energy use had increased to 50 EJ/year. The introduction of electricity as energy carrier (that can supply light, heat and work) and the development of the internal combustion engine triggered the second transition: the introduction of oil as a carrier and later on the introduction of natural gas. At the end of the 20th century, total energy use increased to 400 EJ/year and this amount is supplied by a variety of sources: natural gas, oil, coal, hydropower, nuclear power and wood. It is not unlikely that new changes will occur that will make solar radiation more suitable as an energy source [6].

1.2. Surface available for energy interception

The total surface of the globe is limited which puts an upper limit to the amount of energy that can be gained from the sun. Only about 1/3 of the globe is land,

Table 1
Present global land use expressed in Gha (10^6 ha) and in m^2 per person

	Gha	m^2 per person
Total land	13.0	21,600
Arable land	1.5	2500
Pastures	3.5	5800
Forests/woodlands	4.0	6600
Other land	4.0	6600

assuming that only on a land surface solar energy can be collected, only 1/3 of the total incoming radiation can be intercepted. Table 1 shows present global land use. The total land surface is 13 Gha, 5 Gha is in use for food production. This includes the arable land used for growing crops like wheat, maize, potatoes, etc. and the pastures used for livestock, which provide dairy products and meat. The remainder includes forests and woodland, nature reserves, and barren land like deserts, rocks, etc.

The need for food puts an extra limitation on the potentials for the use of solar radiation for energy. The only way to produce food is by growing crops. In the photosynthetic process, solar energy is converted into structural plant material suitable for human consumption. Although large surpluses of various food items exist on the world market, this does not mean that there is a surplus on food on global scale. The surpluses are due to incorrect distribution of food. The WHO [16] estimates that world wide 800 million people suffer from malnutrition.

Global food supply studies indicate that in near future important increases in food production are required for maintaining the need for food in the world [2]. The increases in production are needed as a result of an increase of the world population on one hand but also due to the increased consumption of luxury food items like meat, sweets and beverages by this population.

This increased production can be obtained by cultivation of larger areas or through obtaining higher yields from existing agricultural grounds.

This paper focuses on the global land claim generated by the food production system on one hand and the energy system on the other. Since large differences occur in energy and food consumption over the world distinction is made between ‘rich’ and ‘poor’ consumption and production situations.

2. Food consumption and production

2.1. Food consumption

The nutritional energy requirements of a human body are about 10 MJ per day. There is not much difference in the intake in energy between developed and developing countries. The composition of the menu, however, shows large differences. The affluent consumption patterns are characterised by consumption of meat and other livestock products, next to this a lot of non-energy food items (coffee, tea, fruit juices, etc.) are consumed that also require land. While in the developing countries, energy requirements are mainly fulfilled with carbohydrates from rice and grains [4].

To quantify the differences between the basic and affluent diets, a method often used in food security studies is adopted. In these studies consumption patterns are often expressed in grain equivalents [11]. A very basic menu of 200 kg of wheat per person per year can fulfill the needs for food. More affluent diets with meat, etc. are estimated to require four times as much grain equivalents. This extra grain is needed as feed for livestock. Here, it is assumed that in the poor situation 200 kg of wheat is needed per person per year and in the rich situation 800 kg per person.

2.2. Food production

The surface required for the production of food depends on the yields obtained. Agricultural yields show a very large variation over the globe, this variation is partly caused by differences in growing conditions but also by differences in the agricultural practices. Especially the use of chemical fertilisers plays an enormous role. Changes in agricultural practices can occur rather fast. In the Netherlands for instance the yields per hectare have doubled since the 1950s [9]. The context of this paper is focussed on wheat. The highest grain yields are obtained in the Netherlands and may reach 10 Mg/ha [9]. The average grain yield in the world is only 2 Mg/ha, while in parts of the world yields are even below 1 Mg/ha (700 kg/ha in Ethiopia [3]). Here it is assumed that in rich situation yields are 10 Mg/ha (1 kg/m^2), and that in poor situation 2 Mg/ha is harvested (0.2 kg/m^2).

3. Energy consumption and production

3.1. Energy consumption

Large differences in energy use exist over the globe. In the developing countries energy use per person is estimated to be 35 GJ/pp/year, while in the developed countries it is 200 GJ/pp/year [7]. Also differences in carriers exist. In developing countries biomass (wood) is still an important energy source (38%), while in the industrialised world it only accounts for 3% of the energy supply. Most industrialised countries use a mix of natural gas, oil, coal and nuclear. Distinction is only made in the total energy use. The poor situation is characterised by the use of 35 GJ per person per year and the rich situation by 200 GJ.

3.2. Energy production for renewable resources

Several renewable energy sources are in use, wind, hydro, photovoltaic and biomass are the most frequently used energy sources. Both photovoltaic as well as biomass directly use solar radiation as the source for their energy, while hydro and wind obtain their energy indirectly from the sun via the hydrological circle and/or the climatic system. This analysis focuses on biomass and photovoltaic systems since they require surface/land to collect the incoming radiation.

3.2.1. Photovoltaic systems

In PV-cells (or solar cells) solar energy is converted into electricity. In principle a PV-cell consists of two layers; the photoelectric effect of solar radiation (photons) creates a difference in electric potential between front and back layer of the cell. This difference is used to generate a direct current. This can be converted in alternating current with the aid of transformer. Several types of solar cells exist for overview is referred to Green [5]. Solar cells are combined to solar modules. Solar modules can be placed at roofs of houses and other buildings and connected to the grid, but stand-alone systems also exist. The efficiency of the systems varies between 5% and 30%, depending on the type of system used. In this paper an efficiency of 15% is used for the calculations, since that is the highest efficiency for presently available systems. The price of electricity obtained from solar cells is 0.6–0.8 Euro per kWh [8,12].

Since radiation levels differ over the globe, the annual yield of a PV-system depends on the location where it is erected. For this analysis the global average data are used: incoming radiation of 5200 MJ/year per m^2. Assuming an efficiency of 15% of the PV-system this would involve an energy yield of 780 MJ/ m^2. It is assumed that efficiency of the systems is independent from its location. The assumptions mentioned imply that energy yields from PV-systems are the same for both the poor and the rich circumstances.

3.2.2. Biomass

In photosynthesis, solar energy is converted into chemical energy (glucose). The assimilation products of the plant (gross primary production) are used for maintenance of the existing plant material and for the production of structural plant material (cellulose, proteins, fats, etc.: the net primary production, NPP). This structural plant material can be used for various purposes. In general, it is used as food or feed, but it can also be used as an energy source. The use of plant material as energy source leads to the emission of CO_2. This CO_2, however, has been taken up from the atmosphere and incorporated in structural plant material by the plant in the preceding growing season(s). The net emission of CO_2 from this energy source is therefore zero. Substitution of fossil fuels with energy from biomass therefore leads to a reduction of CO_2 emissions.

The use of biomass as an energy source is not new, since wood was the most important energy carrier in the past. And as mentioned earlier in developing countries still nearly 40% of the energy used is obtained from biomass. However, unto now biomass is mainly used for heating and cooking purposes. The present western world societies require other carriers and to be of use in a modern society plant material has to be converted. The most frequently mentioned routes are conversion into a transport fuel (biodiesel or ethanol) or into electricity. These conversion processes are not free of costs and require energy themselves. In a comparative study to the suitability of plant material for energy [10], it was shown that use of wood from short rotation forestry systems as a feedstock for electricity generation was the most efficient method (from the energy perspective) to obtain energy from plant material. In short rotation forestry systems, fast growing trees like willow and poplar are planted at a high density (1 tree/m^2). After a couple of years (4–7), the crop is harvested by coppicing. The stubs re-sprout and a few years later the crop can be harvested again. It is estimated that such a system can remain productive for about 20 years.

The highest solar energy use efficiency is obtained when high-input systems are used [13,14]. These systems include the use of heavy machinery, use of fertilisers and pesticides. This type of production system can only be realised on high-quality soils (comparable to soils required for food production). The wood chips are combusted in a conventional coal plant.

The use of fertilisers, pesticides and frequent harvesting makes this production system comparable with high-input agricultural systems rather than with natural forests.

It is possible to grow biomass under low input conditions (no fertilisers, etc.) but then yields drop to about 2 Mg/ha/year and become comparable to NPP in natural forests.

The costs for wood chips as feedstock for electricity plants are estimated at 0.06 Euro per kWh, while feedstock costs for coal are 0.02 Euro per kWh [17]. (Electricity is sold to the households for about 0.13 Euro per kWh, excluding taxes.)

Here, distinction is made between biomass yields in the rich and the poor situation. It is assumed that same differences occur as for food. In the food production system, the yields in the poor situation are low, due to the lack of agricultural knowledge and lack of resources (artificial fertiliser). For obtaining high yields in biomass plantations, the same knowledge and the same resources are needed as for food production. Since this is lacking, biomass yields in the poor situation will be low too. Distinction is made between well-managed plantations where fertilisers are applied, the yields of these plantations are estimated to be 15 Mg/ha [1]. And in unmanaged plantations, the yields of these plantations are derived from the natural wood surveys [15]. Where it was shown that under natural circumstances forests tend to grow 1 Mg/ha per year. The heating value of wood is 18 MJ/kg, multiplying this by the harvest results in the energy yield of such a crop.

4. Land requirements

4.1. Determination of the land required for food

With respect to food production, two systems are evaluated. In the rich system yields are high (10 Mg/ha) and the consumption is affluent (800 kg grain equivalents per person per year) leading to 800 m^2 of good agricultural land per person to fulfill the needs for food.

In the poor system consumption is basic (200 kg grain equivalents) and yields are low. This combination leads to a need of 1000 m^2 per person for food. It is striking that the poor system requires more land than the rich system. This is due to the very low agricultural yields.

4.2. Determination land required for energy

With respect to energy four systems are studied. A rich energy use system (200 GJ/ppa) and a poor energy use system (35 GJ/ppa). For both energy consumption levels, the land area required fulfilling these needs by biomass plantations or by photovoltaic systems is calculated. Table 2 shows the results. As mentioned before, the efficiency of the photovoltaic systems is the same in both the poor as in the rich system. Since the rich system requires six times more energy, the area needed to generate energy with photovoltaic cells is six times larger.

When energy is obtained from biomass a different picture occurs: since biomass yields are low in the poor situation the acreage required for energy in the poor situation is far larger than in the rich situation (over twice as large).

The difference between area needed when biomass is used and when photovoltaic are used is tremendous: in the rich situation biomass crops require 7410 m^2 while photovoltaics 256 m^2. In the poor situation, it is even worse: nearly 20000 m^2 versus 45 m^2.

4.3. Comparison between land required for energy and land required for food

When areas needed for food and for energy are compared, it is shown that photovoltaics use less land than that required for food, however when biomass is used as energy source more land is needed for energy than for food.

When energy is obtained from crops, nearly 10 times as much area is needed for energy generation than for food production. In the poor situation, it is even worse: nearly 20 times more land is required for energy generation. This large area for energy can be explained from the energy and food consumption data. As mentioned before, 10 MJ of food per person per day is needed. This implies 3.6 GJ per year, which is only 10% of the requirements for energy in the poor situation (35 GJ per year). When energy is obtained from the same conversion system as food (the photosynthesis), ten times larger area is needed for energy as is for food.

Table 2
Overview of the consumption and production data used for the rich and poor circumstances and the derived land requirements. All consumption values are per person per year

	Circumstances	
	Rich	Poor
Food consumption (in kg grain)	800	200
Energy consumption (GJ)	200	35
Grain yields (kg/m^2)	1.0	0.2
Energy yields PV (MJ/m^2)	780	780
Energy yields biomass (MJ/m^2)	27	1.8
Land req. for food (m^2)	800	1000
Land req. biomass crops (m^2)	7410	19444
Land req. photovoltaics (m^2)	256	45

5. Discussion

The results obtained in this analysis with respect to land requirements are very sensitive to the yield estimates used. Other assumptions with respect to yields will lead to quite different estimates with respect to land requirements. It is mentioned that yields show very large variations. The assumptions made in this paper with respect to yields can be considered as very course estimates.

The data presented in Table 2 should therefore not be interpreted as estimates of future land requirements. The data presented are just grips to identify factors that play important roles in land use requirements.

In general, the production values used in this analysis tend to overestimate production both for food as for energy. Consumption values are within the presently known range. The calculated land requirements are therefore underestimates. The values presented can be considered as minimal values.

Table 1 also shows the land available per person. Assuming that arable land, pastures and woodland can be used: about 15,000 m^2 is available for both food and energy production. The category other land includes deserts and rocks, etc. It is assumed that the quality of these areas is not suitable for growing plants.

In the poor situation already 19,000 m^2 is needed for energy from biomass (Table 2). Although data cannot be interpreted as estimates they do point to a critical situation. In the poor circumstance, there is not enough land to fulfill the needs for energy when biomass is used as energy source. This situation can actually be found in practice. In large parts of the developing world, a severe shortage in wood for cooking purposes exists. The use of wood for cooking purposes is one of the major causes of the global deforestation.

In the rich situation, the land required is 8200 m^2 for both food and energy and lays below the average globally available area of 15,000 m^2 per person, so that its seems that at least some possibilities exist. However, in that case present forests and woodlands must be converted into biomass plantations. In the introduction it was mentioned that large differences in yields exist between natural forests and biomass plantation. This is due to the fact that for obtaining high yields in woodlands the same practices as in intensive agriculture are required: use of fertilisers, pesticides, high yielding varieties, irrigation, etc. The practices imply large-scale transformation of woodlands into biomass plantations. The social acceptance of such large-scale transformations will be low. Next to this in practice these woodlands are woodland because physical circumstances are not favourable for agriculture: soils are too hilly, too stony or too shallow, etc. these physical circumstances will also limit the possibilities of intensive energy crop plantations. So that possibilities of using biomass as energy source in a rich world are also rather limited. Biomass cannot fulfill the total energy requirements.

The perspectives of energy from photovoltaic cells are much better. Their required areas are only 25% of the area required for food in the rich situation and even less in the poor situation (4.5%). This is due to the fact that efficiencies of PV-systems used in the poor and rich situation do not show differences (the assumption in this analysis) the low energy use in the poor situation results in low land requirements. On the basis of the annual consumption and production data, it is obvious that PV-systems are the only option to fulfill the energy demands. However, the incoming solar radiation shows an enormous variation both over the day and among seasons, the amount of electricity obtained from the PV-cells follows this pattern. The incoming solar radiation in winter is not enough to fulfill the electricity demand in this season and the surplus of generated electricity in summer has to be stored for use in winter. At present there are no energy storage facilities with capacities large enough to solve this seasonal problem. The introduction of PV-systems therefore requires large adaptations of the energy system. The system has to change from a stock driven system to a flow driven system and technological, economical and institutional changes are required. Comparison can be made with changes from energy carriers in the past. It took 100 years before coal replaced wood as the major energy source, and 50 years before oil replaced coal. The transition to a solar driven energy supply system will also require several decades, until then opportunities for electricity from PV-systems are small. The short-term perspectives for energy from biomass are much better, since it fits better in the present infrastructure. The physical limitations imply that biomass can never fulfill all needs for energy in the world without complete destruction wood ecosystems. Biomass has therefore a function as transition fuel. It fulfills the short-term needs for renewable energy sources, but on the longer-term implementation of PV-systems and corresponding change in the energy supply system is necessary.

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