BIOTIC SOLAR ENERGY
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qui nous ont aimablement fait parvenir cet article.

RÉSUMÉ

Le rayonnement énergétique du soleil doit être assez dense et important pour rendre son exploitation économiquement rentable. Malheureusement les radiations à ondes courtes du soleil, source la plus abondante d'énergie renouvelable, est caractérisée par un flux diffus et temporaire.

Ainsi, nous avons besoin d'un système pour maîtriser le soleil qui fonctionnerait sur de grandes surfaces.

Chez les plantes vertes, les mécanismes qui récoltent et stockent l'énergie, croissent et s'entretiennent d'eux-mêmes, automatiquement. On dit que cette capacité unique doit être pleinement utilisée, et des stratégies sur la production d'énergie à partir de la biomasse en sont au stade de discussion. On a mis en évidence un système énergétique où le méthanol est obtenu à partir de bois de saule.

La balance énergétique est hautement positive, et les résultats initiaux indiquent que le modèle aura des applications pratiques.

On développera :
— le flux de l'énergie solaire
— les plantes vertes qui piègent « l'énergie verte »
— les résultats sous climat tempéré
— cas du saule — aspect sylvicole — combustible de haute qualité obtenu à partir du saule
— conclusion.

Waterpower, wind and firewood have their origin in the sun. The solar driven processes have certain unique advantages among the world energy sources if the availability in the long run and the environmental kindness are considered. At present there is an amazing gap between the physical potential and the actual use of the renewable energy from the sun. The average income flux of the solar radiation is more than 10,000 times greater than the statistically documentated consumption of the primary energy in the world (1,2). However, 80-90 percent of the energy consumption is now filled with nonrenewable resources, mainly with oil and coal (2).

The excess of the sunshine exists also on national basis. The developing countries share the greatest potentials, but the industrialized world is not lacking opportunities either, as shown in Fig. 1. Even the most densely populated countries with high standard of living, like the Netherlands or U.K., do not consume more than 1-2 percent of the energy received from the sun. Evidently, the physical shortage would not limit the activities in utilizing the solar radiation. The key factors are the feasibility and the economics.

STREAMS OF THE SOLAR ENERGY

Unlike the other energy sources, the renewable energy is essentially based on streaming processes. Of all the energy flows, a large and rapid river contains the greatest energy flux density. In addition, many rivers contain rather constant fluxes and if not, the problem can be solved by damming. The cycle of water concentrates the solar energy into the rivers. Niagara, for example, is estimated to produce a potential energy flux of 4,400 MW.

The kinetic energy of the wind is created by the stream of air. The average velocity of the near surface wind in the world, 5.85 $m\ s^{-1}$ (3), causes an effect of 130 W through one square meter of a vertical windfacing area (4). If all the wind energy were extracted winds would cease blowing. This strange phantasy restricts the potential of the average wind effect. "The energy extracted in one square meter will not appear in another square meter to be extracted again" (5). Resembling the cycle of water, the process of wind collects and concentrates the energy, although the energy flux density of the wind is far below that of river.

Interesting is that the average effect of the wind almost equals to the energy flux density of the solar radiation whinc has an annual world average of 200 W m^{-2} (horizontal soil surface) (1). The total energy flux of the solar radiation, however, is greater than that of the wind by a factor of 50 (5).

A crucial but largely ignored limitation in the solar radiation is the diffuseness (6). The sunniest part in the world is the Red Sea area with an average solar flux density of 280 W m^{-2}. Even there, an area of almost 1,600 hectares is needed to cover the energy effect of Niagara. In order to obtain this energy effect in terms of electricity the present photovoltaic cells should in fact cover a much larger area.

Hydropower, wind and solar energy are compared in Table 1. Differencies in the energy flux density under favourable conditions explain why the renewable energy is preferably extracted from the flow of water instead of more abundant resources wind and sun.

Another limitation in using the solar energy is the temporal variation. The intermittent and diurnal variations can be levelled out by numerous energy storing systems although there is a cost gap to be spanned (7).

The seasonal variation is a more difficult problem. This is most significant in the temperate zones near the high latitudes. Finland, for example, has to use 60 percent of oil in space-heating during winter. Unfortunately, three quarters of the solar energy falls outside the heating season.

GREEN PLANTS CAPTURE AND STORE SOLAR ENERGY

When realizing the two major limitations in the solar energy utilization, the following conclusions emerge: (i) the system should be easy to spread over wide areas, and (ii) the system should be able to store the energy.

The green plants have a few advantages over any artificial solar energy collectors. First, they have a self-regulative ability to grow and cover wide areas. They build efficient solar quanta collectors automatically.

The foliage also maintains itself selfregulatorily. In a stand of full coverage, the unefficient old leaves are replaced by vigorous new leaves and the stand keeps continuously a leaf area which may be even tenfold compared to the respective soil surface area.

The plants are also able to store the energy; the phytomass—stems, leaves and roots—acts as storage. The photosynthesis contains in principle the energy conversion chain from electromagnetic radiation through electrical energy to chemically bound energy. It is worth notifying that the nature utilizes the advantage of the electricity, but only instantaneously. It is the chemical bond which stores the energy for longer periods.

It could be possible to create a photosynthesis imitator which generates hydrogen and oxygen from water with a simpler set of chemicals that the plants do (8). The imitator would give up the complexity of the green plant to reproduce itself, and just carry out the solar quanta collection and conversion. Unfortunately, the price of this artificial plant is the loss of self-regulation. It will be difficult to build photosynthesis imitators over thousands of hectares to collect notable energy yields.

Plants convert solar radiation into stored carbo-hydrates rather efficiently. Conversion ratios as high as 0.04-0.05 are achieved in crops with record yields (9), if the energy gain is calculated including roots. These are average figures over a whole year, and refer to a process which not only binds but also stores the energy.

Nigh cover a great proportion of time providing no energy input, and part of the captured energy is needed for respiration. We can therefore conclude that instantaneous conversion ratios of fast growing crops match those of the best photovoltaic cells, which are of the order 0.10-0.15 (10).

ENERGY FARMING

Energy farming is a discipline on cultivated plants and husbandry in which the solar radiation is collected and converted into biotic energy of the phytomass. The aim is to obtain high energy yields by selecting, breeding and raising fast-growing crops.

For avoiding competition with the food production the land for energy farming must be sought in different areas than the cereal crop growing zones. There are many possibilities.

The tropics with a reasonable rainfall allows the highest yields. The most high-yelding agricultural crop in the world has been reported to be the sugarcane (11). It has also the advantage in form of the stored energy; sugar is easily fermented to ethanol.

In the wet tropics, a sugarcane-ethanol system could yield (gross production) up to 8,000-9,000 kg ha^{-1} a^{-1} ethanol (12). However, although sugarcane as a C_4-plant is moderately efficient in water use (13), the rainfall requirements restrict the suitable growing areas. Generally, the yields would not be economically profitable without irrigation in the areas where the rainfall is less than 2,000-2,250 mm annually (14).

Another sugar crop, pineapple, is adapted to the drier tropics. Due to the crassulacean acid metabolism (13) the pineapple crop utilizes the soil water twice as efficiently as sugarcane. The annual rainfall requirement is only about 1,000 mm, but the ethanol yields would be of the same order as with sugarcane (12). Such a rainfall is received over wide areas in the tropics. The Cerrado of Brazil with approximately 170 millions hectares has been mentioned as a suitable pineapple growing area.

The tropical forests offer a multitude of unexploited possibilities of environmentally lenient high-yielding energy-forestry. The "giant ipil-ipil" (*Leucaena leucocephala*) is a good representative of both the potential as well as the problems so far involved in the use of tropical tree species in energy-forestry (15).

Due to the geographical distribution of the land area the main part of the world's energy farming area must be sought in the northern hemisphere. Here the low evapo-transpiration results in an excess of water over a large zone, although the annual rainfall is usually below 1,000 mm. Moist soil accumulates humus and forms peat. The peatlands are largest in Siberia and Canada.

The northern peatlands can be regarded as one of the most remarkable energy farming areas waiting for the clearing for cultivation. With present machinery a proper drainage of the peatlands is easily arranged and the excess of water is no more a problem.

The total area of the peatlands in the world has been estimated to be at least 230 millions hectares (16). Part of it belongs to the tundra zone, but if every other hectare of the world peatlands could be utilized, the area still equals for instance to the present agricultural area of the U.S. (17).

ENERGY CROP IDEOTYPE IN SEASONAL CLIMATE

In the boreal zone the growing season is short but rather favourable. There is plenty of solar radiation available due to the long summer day, and the daily temperatures are moderate. The winter is severe. There is no need of sparing water.

The ideotype should have an efficiently photosynthesizing foliage ready in the spring waiting for the temperatures high enough for carbon fixation. The crop should maintain a high growth rate during the whole summer. The wintering until the next growing season should be safe. Obviously no present, conventionally grown crop meets all these requirements.

Conifers have their evergreen needles ready in the spring, but their period of high growth rate is strongly reduced by the winter hardening process in the latter part of the summer. This process is shorter in deciduous trees, but they must establish their foliage again after every winter. Certain annual hay plants, like Italian ryegrass (*Lolium multiflorum*) can photosynthesize with high efficiency until the autumn frosts, but they must start from the seed every spring. The ideotype is doomed to be a compromise.

Some additional properties for the ideotype can be listed. The crop must be easily established. A clonal propagation is preferable due to the genetic homogenity. Once established the crop should sprout from the roots after the harvest. The roots must endure several cuttings and winter safely.

CASE WILLOW

Promising clones for northern energy farming can be found in the genus **Salix**. There are about 300 willow species in the world (18). Most of them cross freely in the nature and the number of hybrids is overwhelming. At present they are wild plants, and as such they are suitable to start with the energy crop breeding.

Energy willow farming was developed in Nordic countries in mid seventies. It has its modern origin in the concept of mini-rotation forestry (19). In the begining the aim was only to produce more raw material for the wood industry, using methods as intensive as in the agriculture.

The first field experiments in Finland and Sweden were established in 1973. Promising results were obtained at once. A Danish willow clone, **Salix** cv. "Aquatica" produced in the latitude of the arctic circle a dry matter (DM) yield of about 10 tons ha $^{-1}$ already in the first summer (20).

In the later experiments more willow species have been screened both in Finland and in Sweden. The annual yields have kept their high level. The biggest dry matter yield reported (21) has been 32 tons ha^{-1} DM per year which includes the harvested stemwood only.

The energy willow farming can be divided in two groups according to their wintering ability. If the clones used are completely frost resistant they are grown like any other deciduous crop; the rotation cycle will vary between 2-5 years. If the shoots do not winter but the stumps and roots do, one year rotation is used.

So far it is not sure which one of the two practices will result in highest yields. In a many-year rotation the dormancy reduces autumn photosynthesis, but in early summer the foliage develops rapidly on already existing shoots. Applying one-year rotation the early season growth is slower. However, when there is no need of winterhardening, the leaves continue carbon fixation at a high rate to the autumn frosts. The active period of the willow in one-year rotation lasts until October. The period is about one month longer than that of birch.

In central and southern parts of the Nordic countries the 2-3 years rotation will probably give the highest yields. Moreover, many-year crops seem to produce à more energy-rich and structurally better fitted shoots for the cutting devices of the future harvesting machines (22).

Aspects on willow husbandry. The energy willow has the advantage of the clonal propagation. The crop is established using cuttings. After the first harvest the willows will coppice 5-20 shoots per one cutting, depending on genetic differences between the clones.

The planting density connected with the coppicing ability has a clear effect on the yield. The main rule holds that the bigger the number of vigorous shoots, the bigger the yield will be (23). As a practical compromise, we aim at shoot number 30 per one square meter in one-year crops. With this a full coverage is established within 30 days in the spring.

As a husbandry method, a special row cultivation can be recommended in such a manner that ordinary tractors can operate later on without damaging the stools. The planting as well as harvesting are cheaply mechanised.

The ash plays an important role in the recirculation of the nutrients (22). Actually, if the energy crop yield is burned in a heating plant, main part of the nutrients can be returned to the plantation in the ash. Nitrogen escapes to the atmosphere; minor potassium losses have also to be compensated.

Here and later on a practical example of Salix cv. "Aquatica" cultivation with a moderate stem yield of 12 tons ha $^{-1}$a $^{-1}$ DM, or 197 GJ in energy terms (24) will be used. The leaves which contain a considerable amount of circulating nutrients fall annually as litter to the ground.

The ash and nitrogen content in the stems of the energy willow are 2.5 and 0.75 percent, respectively. Thus the removals are 300 kg ha $^{-1}$ for ash and 90 kg

ha^{-1} for nitrogen. At least these amounts should be returned to the willow plantation annually to maintain the nutrient balance.

Nitrogen is fixed to the fertilizer from the atmospheric resources using a certain amount of energy. It has been estimated that the whole chain of nitrogen from the atmosphere through the factory to the field needs an energy input of 77.0 MJ per one nitrogen kilogram as fertilizer (25). The nitrogen fertilization of 90 kg ha^{-1} will thus require an energy amount of 6.9 GJ. Therefore a part, in this example 3,5 percent, of the gross energy yield must be reserved to keep the nitrogen cycle going between the atmosphere and the energy plantation.

The nitrogen fertilization seems somewhat high. If a suitable peatland is selected for the energy willow, the nitrogen dose can be reduced to the half. The fertile bottom peat contains often more than two percent nitrogen in its dry matter. In a cultivation layer of 30-50 cm, there are nitrogen reserves for 100 years energy farming if reliable means to mobilize the nitrogen are found out.

The ash fertilization has a central role also in the nitrogen mobilization. It has been found in Finnish peatland fertilization experiments that the activity of bacteria, espeacially with ammonifiers increases dramatically after the ash fertilization. As a result, the nitrogen mobilization speeds up. Due to this effect we can reduce the nitrogen fertilization. However, some mineral nitrogen is needed as a booster for the early summer growth, when the temperature is too low to maintain a high activity of bacteria.

The fertilization is one of the biggest parts of the energy inputs in the energy willow husbandry. Since the willow plantations are still in an experimental scale we estimate the other inputs needed on the basis of information from a resembling husbandry with other crops (Table 2). The total agricultural input in the energy willow may be of the order 20 GJ $ha^{-1}a^{-1}$. This level corresponds for instance with the intensive **Populus** "tristis" husbandry of Zavitkovski (25), but without irrigation.

High-Grade fuel from energy willow. The energy willow system can work as an energy amplifier in terms of high-grade fuel. We choose methanol as the alcohol, since the present technology converts methanol from wood more efficiently than ethanol.

As a basis for the calculation we use a recent plan to convert Finnish peat fuel into methanol (28). With minor adjustment the proposed plant accepts also any other form of the phytomass than peat as a feedstock. The approach and notations are from Weisz and Marshall (29).

The agricultural input in high-grade fuel is denoted with **A** and the gross energy yield with Y_0. The input—output ratio f expresses the efficiency of the crop and of the husbandry practised ($f = A/Y_0$). In the example, A = 20.0 GJ, Y_0 = 197 GJ, and f = 0.102. In other words, the energy input is 10 percent out of the crop energy output.

Methanol can be produced by the partial combustion of the willow phytomass with oxygen and steam. The conversion plant is self-sufficient in energy. Part of the incoming willow yield is burned in a counter-pressure power plant. The electricity needed in the conversion process is thus created by the plant itself.

The methanol plant is assumed to produce 359 grams methanol as output, for every kilogramm DM of the input. Thus the 12,000 kg of the willow going into the conversion, yield 4,310 kg methanol. Using the heat of combustion value 20.1 MJ/kg, the methanol output corresponds G = 86.6 GJ (Fig. 2.)

The energy willow-methanol system works as an energy amplifier (in high-grade fuel) since the output exceeds the input. Part of the solar energy flux, 177 GJ for the hectare of our energy willow has been converted into liquid energy form. The amplifying effect (G/A) is 4.33.

The fraction **n** expresses the efficiency of the methanol conversion, $n=G/Y_0$, in the example n=0.440. The net productivity **N** of the system is the difference between the output and the input N = G − A, in the example N = 66.6 GJ, or 3,310 kg ha^{-1} methanol.

A capacity of 1,000 tons day^{-1} methanol for the factory has been considered suitable. In the Finnish conditions this capacity could provide a mixture of 15 % methanol needed by all the one million cars in the traffic.

With the yield level of 12 tons ha^{-1} DM the area needed to satisfy the raw material demand of the factory would be about 111,000 ha. It is five percent out of the total area under agricultural crops, and 0.6 percent of the forestry land in Finland.

The calculations above are based on a moderate yield estimate and the present day methanol technology. Both of these system components can apparently be improved.

In southern Sweden the yield level of 18 tons ha^{-1} DM has been achieved on areas large enough for reliable calculation (22). Thermo-chemical processes developed in Sweden for conversion of wood into methanol indicate outputs exceeding 50 percent in the energy efficiency (30). Assuming both these improvements, the net productivity will more than double and exceed 9,000 kg ha^{-1} methanol.

The high net productivity of the energy willow—methanol system at a latitude corresponding Alaska is somewhat amazing (Table 3). The net production of ethanol from sugarcane yields in Louisiana 2,600 kg ha^{-1} (31). Using the average U.S. corn yield of about 5,700 kg ha^{-1} as the yeld level, the net productivity of one corn hectare is only 410 kg ha^{-1} ethanol (29). The use of corn as the raw material for liquid fuels seems thus less attractive activity and wasting of edible photosynthates (32).

The net productivity of the pineapple growing in the tropics is higher, about 6,800 kg ha^{-1} in ethanol (13). This is of course due to the continous growing season. The conversion efficiency to ethanol is also much higher when sugar is used instead of corn starch.

INTENSITY IN ENERGY FARMING

Even a single species crops may be cultivated more or less intensively. Common characters of the agricultural intensity are the input—output ratio $f = A/Y_0$, and the net energy yield $N^e = Y_0 - A$. Two recent but conflicting views will be discussed.

Burwell (17) has found that the input—output ratio correlates positively with the gross energy yield. He concludes that the energy input should be allocated to the traditional forestry where it gives the greatest relative energy output.

Fig. 3. shows, however, that the relationship between f and Y° is not too distinct. The suggested graph fails to predict the additional data.

Parenthetically, a naturel stand of reed (*Phragmites australis*) has produced an annual yield of 11,500 kg ha $^{-1}$ DM (33). Additional agricultural energy input to raise this crop seems inadequate. The harvesting trials have resulted in an energy consumption of 5.2 GJ ha $^{-1}$ (34). This is 2.7 percent of the gross energy yield.

The willow data are from the above example and from the experiments with the highest yield reported (21). The input—output ratio f = 0.1 has beenassumed.

The obvious relationship between the original data points exists maybe because the crops have been raised for other purposes than for energy production. The four energy-efficient exceptions are a promise to the plant breeding. It should be possible to breed special energy plants since the reed and the willow, for instance, actually are still wild plants.

Zavitkovski (25) defences an opposite view than Burwell. He shows that despite the higher f the net energy yield of the intensive tree farming exceeds that of the traditional forestry. He prefers high level of intensity since "it is net energy that counts". Social and economical realities tend also to favour the intensive cultivation in which the land is used effectively. Income received from plant stand is not proportional to the input—output ratio, but to the net yield.

Moreover, methods with high net energy returns must be chosen, if ambitious national goals for the biotic solar energy are set. In U.S., for example, the annual biomass production including food and fibre (in energy equivivalents) would provide only 25 percent of the current energy requirements (25). On the other hand, if existing agronomic technology were applied to fast-growing trees, one third of the U.S. land area would satisfy all the energy requirements.

To conclude, it seems possible to choose highly productive plant species and cultivation methods with a relatively low energy input—output ratio. The ratio, however, should not be minimized at any cost. The criterious in selection of the bioenergy strategies should not forget social and economical consideration.

SOLAR ENERGY STRATEGIES

One may argue that our view is ambivalent. We prefer green plants to more efficient artificial means for collecting solar quantas. At the same time we defend the intensive energy farming against less efficient traditionnal forestry.

The input of material and labour seems, however, tolerable as long as the solar energy system uses the ability of the plants to grow and maintain automatically the structures for collecting, converting and storing the energy. As soon as artificial technological solar strategies, like photovoltaic cells or photosynthesis imitators take over, an abrupt increase in the costs of building and maintaining the solar energy systems will occur.

CONCLUSIONS

There is a common objective that man should become less dependant on nonrenewable energy sources. Alternative paths are Plenty. The proper selection of the most promising strategies could be helpful in concentrating future R & D efforts. Although the knowledge on the solar energy possibilities is still insufficient it is becoming possible to roughly separate "the promising" and "the less promising" strategies for the utilisation of the renewable energy (5).

In our view the energy plantations belong to the promising ones. In this paper we show that recent doubts about the energy balance of the biotic solar energy are based on either misleading generalizations or a special case where the production chain has not been optimized in energy terms.

The production and utilization of the biomass energy consists of a series of well established techniques. The principales of the different phases are already known but combining the details will take time. The combinations are many, depending on the climate and on the social structure, and on the level of technology and plant husbandry. The optimization of the biomass energy chains will be an endless task for systems analysis. In the practice, the production, transport, and industrial conversion processes will acquire more cooperation between different groups of people than is the case with the conventional energy sources.

Our conclusions are based on calculations and small scale experiments rather than verifications in the practice. Now as the framework is becoming clear, it is possible to start with planning practical applications. Fortunately, there is a plenty of conventionally grown biomass available for energy production. The methanol conversion, for example, could start using the phytomass already existing. Meanwhile, there is still time to develop the techniques of the energy farming.

On a global scale there will be no uniform type of the energy plantations. Local case studies are necessarily needed, although some general strategies may be derived separately for the wet tropics, drier tropics and seasonal climate. Combining the energy farming to the food production may cause difficulties in the land area allocation. However, there is some hope left. According to a recent estimate (35) there still is an area of 1.802 10^9 hectares on the globe possible to clear for cultivation. On this area the moderate net energy yield 167 GJ ha $^{-1}$a $^{-1}$ of our example would sum up to 3.0 10^{20} J a $^{-1}$. It is of the same magnitude than the present global energy demand.

Crop	Crop yield kg ha $^{-1}$	Agricultural input GJ ha $^{-1}$	Reference
Alfalfa	6,450 (dry)	11	24
Potatoes	26,200 (wet)	37	24
Maize silage	30,200 (wet)	23	24
Pineaffle	101,000 (wet)	48	13
Wheat	3,000 (dry)	14	25
Hay	5,000 (dry)	13	24
Populus tristis	16,600 (dry)	27	22
Jack pine	11,900 (dry)	19	22

	G/A	N kg ha $^{-1}$a $^{-1}$
Corn—ethanol	1.55	410
Pineapple—ethanol	3.82	6,800
Willow—methanol	4.33	3,300

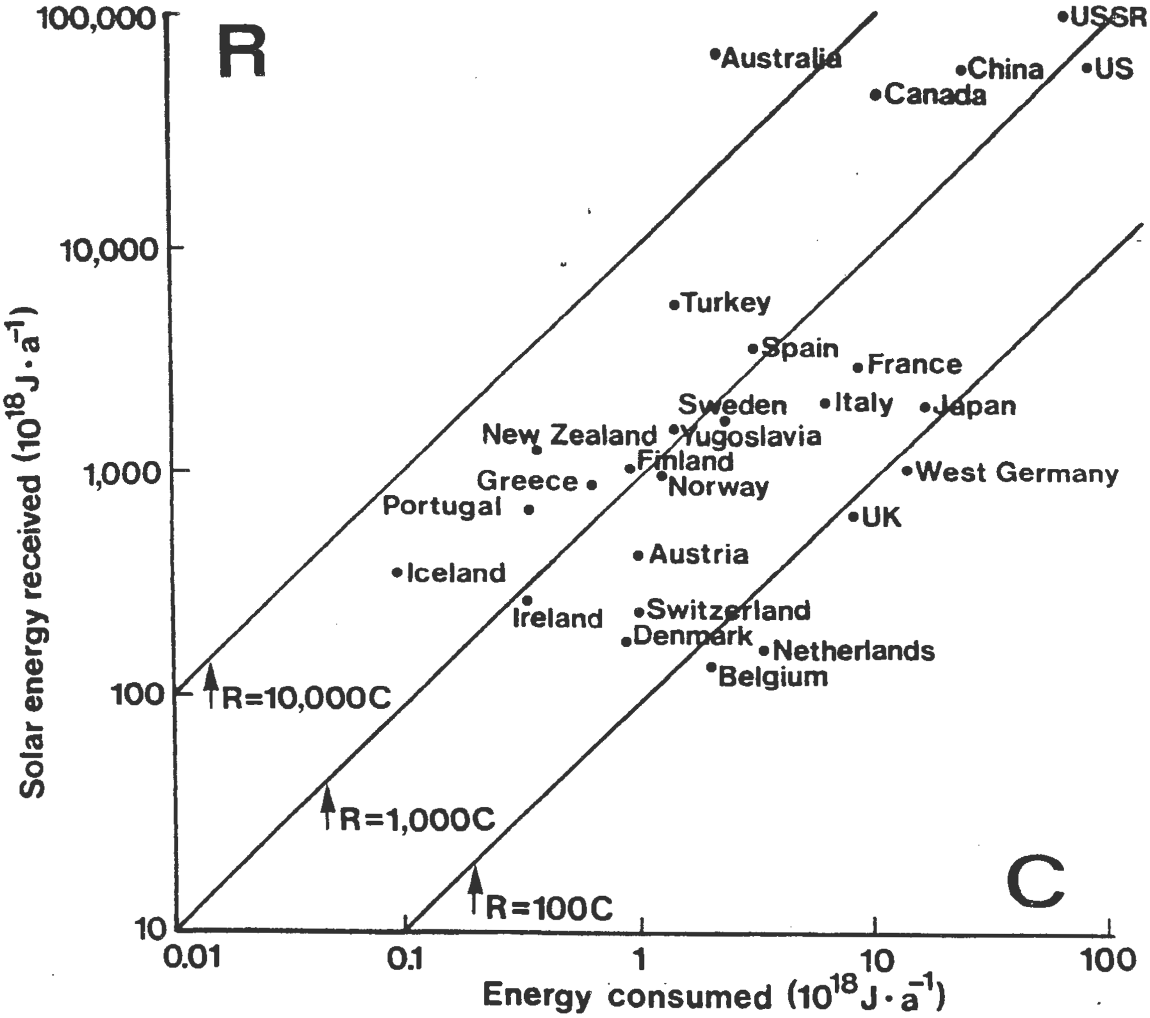

Fig. 1

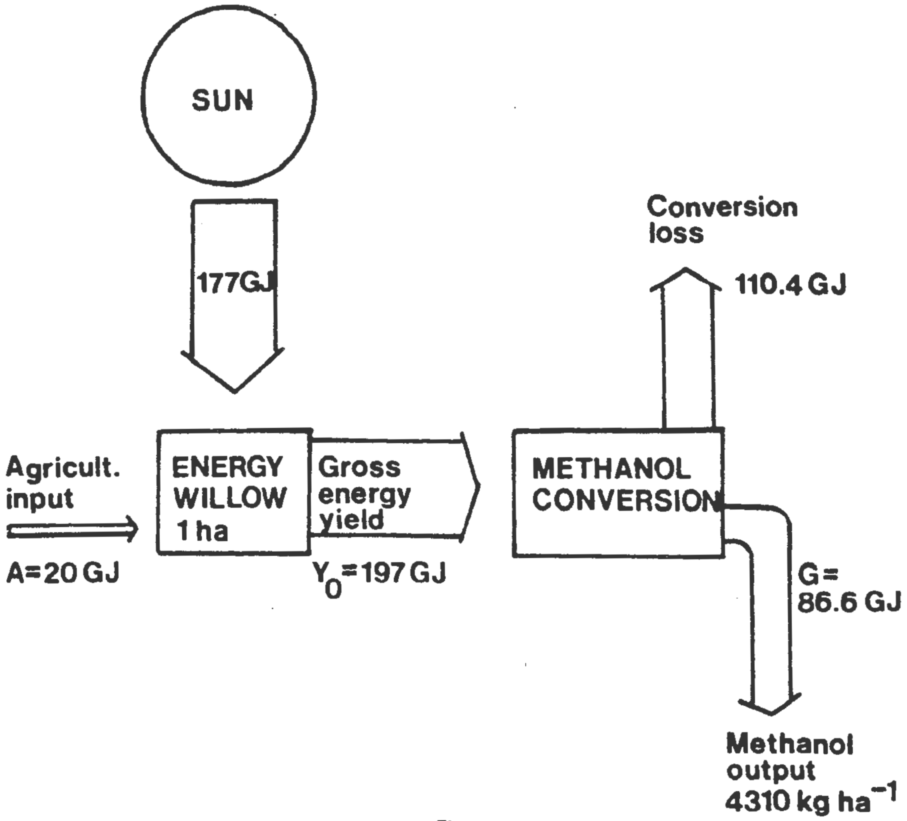
SUN
177GJ
Conversion loss
110.4 GJ
Agricult. input
A=20 GJ
ENERGY WILLOW 1 ha
Gross energy yield
Y0=197 GJ
METHANOL CONVERSION
G= 86.6 GJ
Methanol output 4310 kg ha-1

Fig. 2

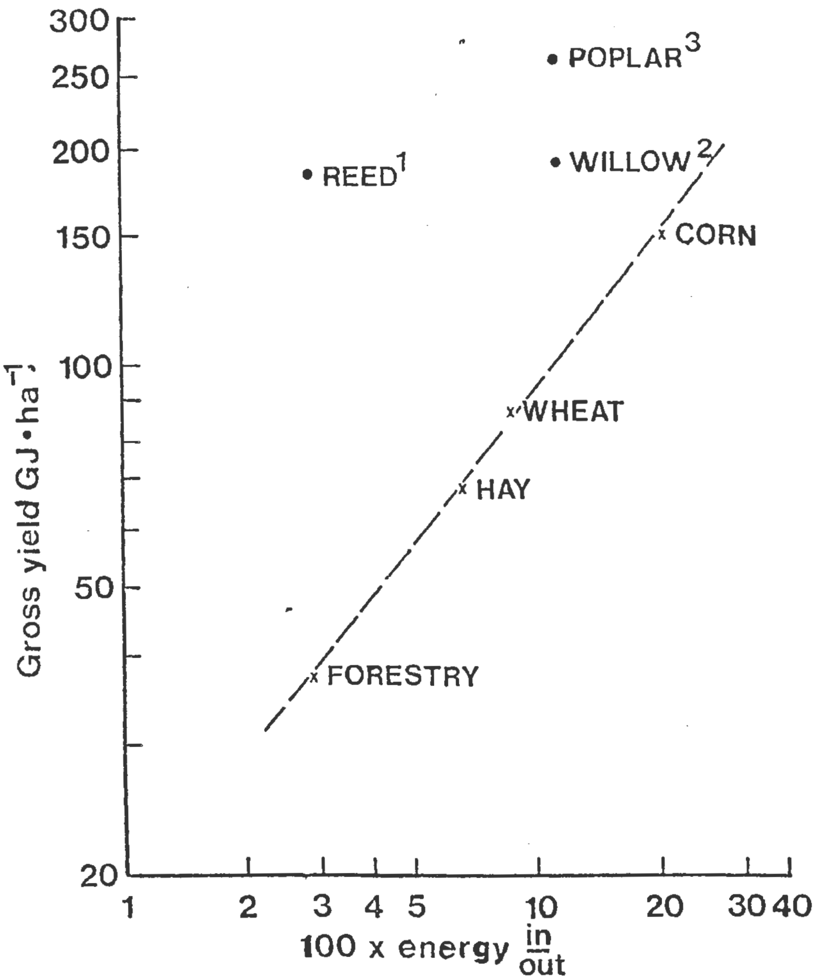
POPLAR 3
WILLOW 2
REED 1
CORN
WHEAT
HAY
FORESTRY
Gross yield GJ • ha-1
300
250
200
150
100
50
20
1
2
3
4
5
10
20
30
40
100 x energy in/out

Fig. 3

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34. Diesel fuel consumption for the harvest $40\ kg\ ha^{-1}$, or $1.7\ GJ\ ha^{-1}$, manufactoring the machines twice that or $3.5\ GJ\ ha^{-1}$, together $5.2\ GJ\ ha^{-1}$.
35. J. Lag, Proceedings of the 16 th NFJ-Congress, Oslo, Norway (July 1979).