Formas Fokuserar

Bioenergy
– for what and how much?

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How long will bioenergy last for the energy systems of the future? How much can we get out of forests and agricultural land – and what should we use it for? Is it wise to use it for conversion into automotive fuel, or should it be used for generating heat and electricity? What regulatory instruments are needed for increasing the use of bioenergy? What conflicts will there be between increased biofuel production and various environmental targets? How is the supply of food doing out in the world? And how good are the bioenergy in actually preventing climate change?

How do Swedish researchers view the issue? Read this book to find out.

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Introduction

How far will bioenergy suffice in tomorrow's energy system? How much could be available from forests and agricultural land – and what will we be using bioenergy for? Is it wise to use it for conversion into automotive fuel, or should it be used for generating heat and electricity? What regulatory instruments are needed for increasing the use of bioenergy? What will the conflicts be between increased bio-energy production and various environmental targets? What is the global food supply situation? And how beneficial are bioenergy in actually preventing climate change?

Bioenergy is a vast resource in Sweden. This was determined by the Commission for Oil Dependence set up by Prime Minister Göran Persson in its report presented in 2006. The targets in the report for the year 2020 were that Swedish dwellings and premises should be heated entirely without oil, that the consumption of gasoline and diesel oil for transport should be reduced by 40–50 percent, and that the industrial consumption of oil should be reduced by 25–40 percent. The Commission has calculated and arrived at the conclusion that Sweden should be able to use more than 40 percent more bioenergy by 2020 than it did in 2005, and that the bioenergy used by 2050 could be more than doubled compared to 2005. The target was that 12–14 TWh (terawatt-hours) of domestic liquid biofuels should be available by 2020, compared with around 2 TWh in 2005.

So how realistic are the Commission's proposals? Will agricultural land and forest raw materials be sufficient? Is it sensible to use agricultural land for energy crop production? Several of the chapters in this book underscore the fact that the available land limits the bioenergy production, and that it is important to take into account how much useful energy can be obtained per hectare. So how important will bioenergy be in the future, bearing in mind that land and raw materials can be used for applications other than energy and if we bear in mind how efficient the various bioenergy systems are?

Typical for Sweden

The book deals almost exclusively with Sweden, and it is therefore advisable to know a little about what is typical for the country as regards energy supply.

Sweden is a small country with around 9 million inhabitants, and everyone knows everyone else in a given subject area. This simplifies the dialogue between the authorities, companies and researchers. The country is in Northern Europe, is around 1600 km long and is fairly sparsely populated. The country is densely forested, has an active forestry that endeavours to find a balance between the environment and production, and where bioenergy is integrated with both forestry and the extensive forest industry. Sweden has a high heat requirement that, in combination with an extensive district heating system, provides an excellent base for effective combined heat and power (CHP) generation from solid biofuels. Environmental targets permeate all of the activities, and there is a fairly strong consensus of opinion that land can be used in a sustainable manner.

Hydropower and nuclear power account for most of the electricity generated and therefore give rise to fairly low emissions of carbon dioxide. Today's Swedish energy policy restricts the uncontrolled expansion of nuclear power. There are also various regulatory instruments for carbon dioxide. The country has an interconnected electricity network.

Sweden is located in Northern Europe. The country is about 1600 km long and consists of the regions of Götaland, Svealand and Norrland.

In a few general chapters at the beginning of the book, researchers with various orientations write about the bioenergy potential both globally and in Sweden.

Biomass – a scarce resource in the global perspective

We are now using around ten times more fossil energy than bioenergy in the world. The bioenergy available globally is insufficient to replace the fossil fuels, write Göran Berndes, Julia Hansson and Stefan Wirsenius at the Department of Physical Resource Theory at Chalmers University of Technology. How should we use the scarce resources in the best way? And how will we be able to restrict the negative effects that the increased demand for bioenergy may have? This concerns, for instance, the exploitation of valuable ecosystems such as rainforests.

Today's challenge – to create a highly productive economy that is independent of fossil fuels and nuclear power – is comparable with the industrial revolution, write Ann-Kristin Bergquist and Magnus Lindmark at the Department of Economic History at Umeå University. The difference is that we can now use political regulatory instruments for making the change quickly, whereas the industrial revolution spanned a period of more than a century and was driven by the small decisions of individual players. Since bioenergy competes with food production, the authors do not believe that bioenergy are a realistic strategy for achieving long-term climate objectives. It is better to direct the focus and resources now onto radical technical changes that will be necessary in the long term.

Biomass in Sweden
– a vast but still insufficient resource

The forest in Sweden will always be a much greater source of bioenergy than arable land. But however much we endeavour to increase the production of bioenergy from agriculture and forestry using traditional methods, the availability in the future will be unable to meet the demand. If the biological potential of the forest is to be put to full use, rules and attitudes must be changed in matters such as fertilization, clonal forestry and foreign tree species, write Energy Researcher Pål Börjesson at Lund Technical University and Forest Researchers Sune Linder and Tomas Lundmark at the Swedish University of Agricultural Sciences (SLU).

Trade in biomass fuels is likely to increase in the future. The bioenergy imports into Sweden are so far higher than the exports. But this may change as the demand in other countries increases. Provided that biomass fuels are produced and transported in a sustainable manner, they will be one of the most important tools for coming to grips with the energy and environmental problems of the 21st century, write Bengt Hillring and Olle Olsson at the Department of Bioenergy at the Swedish University of Agricultural Sciences.

The trend today is that we are shifting from oil dependence to alcohol dependence in fuelling the transport sector, writes Magnus Blinge, Department for Logistics & Transport at the Chalmers University of Technology. Engine alcohol may be one of tomorrow's fuels, although the risk is that we may be binding our investments in technology and systems that are not the best in the long term. He states that about one thousand large and efficient bioenergy plants would be needed to replace all of the fossil automotive fuels in the EU. We must begin planning now the siting of the plants and the transport facilities, since this takes time and will give rise to many conflicts.

Appraisal of bioenergy systems

Since bioenergy is a limited energy resource, we must do our best to use it efficiently. The more efficiently we can use bioenergy, the more we will be able to reduce our oil dependence and our carbon dioxide emissions. With today's technology, it is climatically more efficient to generate heat and electricity than automotive fuels from biomass, writes Leif Gustavsson, Institution for Technology, Physics and Mathematics at the Mid-Sweden University. But new technology is coming and will improve the climate efficiency of automotive fuels.

How should solid biofuels be used as efficiently as possible? Should we use them for generating electricity and heat, or should we convert them to vehicle fuel? It would be difficult to make a general assertion, writes Pål Börjesson at Environmental and Energy Systems at Lund University. But what is certain is that forest fuels, energy forest and unused residual products are efficient in terms of energy, the environment and costs. Moreover, it appears efficient to use biorefinery concepts in which many different commodities can be produced simultaneously, including heat, electricity and vehicle fuel.

Torbjörn Rydberg at the Swedish University of Agricultural Sciences analyzes bioenergy systems in a more comprehensive and far-sighted manner than is usual in today's energy analyses, of which he is critical. He also considers the energy that drives people's work, such as food, and the energy that is used but is regarded as free of charge by the economic system, including solar energy. He comes to the conclusion that an industrial society such as ours is today cannot be run with renewable energy. We must cut down our demands on the Earth's resources.

Which types of energy system are best? To answer the question, researchers use various methods of analyzing the systems. But even if they analyze a given energy system, they seldom arrive at unequivocal answers. The fact that the debate is sometimes overheated and the source information is contradictory does not make matters simpler for our decision-makers, writes Theo Verwijst at the Swedish University of Agricultural Sciences. So how should we set about to arrive at clear and unanimous answers that lead appropriately to the development of the energy systems we want? He hopes and believes that the promoters of different analysis methods will find it easier to understand one another in the future.

Bioenergy in gaseous form

Gasification of biomass is a blend of old and new technology, which is predicted to have a dazzling future. Many different solid biofuels can be used, the technology is usable on both a large and a small scale, and its efficiency is high for large systems. The synthesis gas produced is a key raw material for the production of second-generation automotive biofuels. Advanced gasification technology is also a key technology for a possible hydrogen-based society geared around biomass as an energy resource, writes Erik Rensfelt who has been researching and developing the gasification of biomass since the 1970s.

The biogas process is also a blend of old and new technology used in different scales. It provides three commodities: waste treatment, energy and fertilizer. Currently, Sweden produces only 1.3 TWh of biogas every year, barely one half of which is produced in municipal sewerage treatment works. The technical potential in Sweden is between 10 and 20 TWh, and 80 percent of the raw product can come from agriculture. If the potential is to be exploited, various players must collaborate more effectively – from the grower to the supplier. This is the contention of Åke Nordberg at JTI – the Swedish Institute of Agricultural and Environmental Technology.

Different ways of extracting more raw material from the forest

In the long run, it is not possible to increase the extraction of bioenergy from the forest without affecting the supply of raw material to the forest industry. If the forest is fertilized as necessary, however, it is sufficient for both industry and energy, write Sune Linder, Johan Bergh and Tomas Lundmark at the Swedish University of Agricultural Sciences. With fertilizing adapted to needs, spruce stands in Västerbotten in Norrland produce as much as fertile stands in Skåne in southernmost Götaland. In addition, the nutrients do not leak into the groundwater. Despite this, this kind of forest fertilization is controversial and is not recommended by the Swedish Forest Agency.

Improving forestry by breeding is an effective way of increasing growth in the forest. By including biotechnology methods in the breeding programme, it is possible to increase forest production considerably and more quickly, writes Sara von Arnold at the Department of Plant Biology and Forest Genetics at the Swedish University of Agricultural Sciences. The yield from highly improved and intensively cultivated forest should in the short term be able to increase by 50 percent. The larger the area set aside for more intensive forestry with trees improved by breeding, the more bioenergy we can extract from the forest.

Branches, tops, stumps and small trees – this is the range of products from the forest that can be utilized as fuel. In Sweden, only branches and tops have so far been utilized on a major scale. The hope is that extraction will increase. Handling in the supply system must, however, then be much more effective and the catchment areas must become greater. This subject is discussed by Anna Furness-Lindén, Berndt Nordén and Magnus Thor at Skogforsk.

Is wood burning dangerous?

Many wood burners in single-family houses in Sweden currently emit volumes of different substances that are dangerous to the environment and health. However, small-scale burning of solid biofuels need not be dangerous to humans and the environment. It is a question of having the right equipment, using it correctly and employing a good fuel, according to Bertil Forsberg, Umeå University, and Lennart Gustavsson and Linda Johansson at SP Technical

Research Institute of Sweden. Wood burning licences and dust filters on chimneys may also be part of the solution to the health problems of wood burning.

Energy or industrial crops from arable land?

Salix on arable land can benefit the skyline, increase biodiversity, treat sewage and purify soil, and reduce carbon dioxide emissions, according to Pär Aronsson, Martin Weih and Inger Åhman at the Swedish University of Agricultural Sciences. Currently, chips from salix cultivation account for less than a tenth of one percent of Sweden's energy supply. However, such cultivation is expected to increase once the machines improve and the price of bioenergy rises. Sweden currently exports plant material, cultivation technology and machinery to countries in greater need of bioenergy than Sweden.

Energy forest, reed canary grass and hemp – or grassland, cereals and oil plants? What is it that induces a farmer to choose crops? What is economically worthwhile? And what is the situation in terms of employment? It is hard for new crops at the start. A paradox is that the greater the demand for bioenergy, the more profitable it becomes to grow traditional crops, writes Håkan Rosenqvist, who is linked to both the Swedish University of Agricultural Sciences and to Lund University.

Agricultural crops should be used as raw materials for the chemicals industry rather than for energy production. The appeal comes from Leif Bülow at the Department of Chemistry at Lund University and Sten Stymne at the Swedish University of Agricultural Sciences. We should concentrate on replacing the eight percent of fossil oil that goes to the chemicals industry with competitive agricultural products. We might in the future see industrial beet and energy forests that also produce vegetable oils – or maybe even plastics.

Advantages and disadvantages of environmental targets

How does increased bioenergy production go together with the conservation of biodiversity? Urban Emanuelsson at the Swedish Biodiversity Centre presents a strategy with four main prongs. One prong entails devising new systems that generate high levels of both bioenergy and biodiversity. Another instead entails producing bioenergy intensively on certain lands and biodiversity on other land.

Forests are a limited resource that must stretch to more and more applications. Not least, the demanding aims set out in the environmental objectives of "Limited climate impact" and "Living forests" will lead to conflicts of aims between nature conservation, climate measures and the forestry industry.

Clear winners in this scenario are those who own forests and can enjoy ever higher values of their forests, writes Political Economist Runar Brännlund at Umeå University and Forest Economist Bengt Kriström at the Swedish University of Agricultural Sciences.

If we extract more biomass from the forest for use as an energy raw material, this promotes one of Sweden's sixteen environmental aims, namely "Limited climate impact". And biodiversity tolerates increased removal of branches and tops in connection with felling, writes Gustaf Egnell at the Faculty of Forest Science at the Swedish University of Agricultural Sciences. At the same time, the increased extraction may have consequences in the form of more acidic soil and water, thus posing risks to fauna and flora. Recycling wood ash can be a way of raising the pH of surrounding water in the long run.

Kristina Holmgren and Mats Olsson, together with colleagues at IVL Swedish Environmental Research Institute and the Swedish University of Agricultural Sciences, have compiled and analyzed emission data for production and usage chains for a number of biofuels. They conclude that none of the biofuels investigated can be called "climate-neutral" because all fuel chains result in net emissions of greenhouse gases. They also conclude, however, that biofuels result in considerably lower emissions of greenhouse gases than fossil fuels, and that they can therefore be used to replace fossil fuels.

Are there any climate benefits from making buildings with wooden frames as compared with concrete frames? Yes there are, according to Leif Gustavsson at the Mid-Sweden University, who reports the results of comparative analyses of concrete and wooden buildings. Wood-framed buildings produce lower levels of carbon dioxide emissions in production. To exploit the climate benefits fully, it is important that the biomass byproducts from the wood product chain are used as fuel to replace fossil fuels.

Selecting the regulatory instruments

It is likely that biomass will assume great significance for a transition to a more sustainable global energy system and also form an important part of such a system. It is less likely, however, that biomass is the universal saviour that it is sometimes portrayed as being in Sweden. With the right choice of technology-neutral instruments, we have the opportunity of leaving the doors open to better future technology and an effective bioenergy system, writes Åsa Löfgren, who is a Political Economist at University of Gothenburg.

If the EU targets for bioenergy use are to be achieved, the rules must be designed so that they actually support the growth of sufficiently large industries. The plans call for investment of the order of 1000 billion Euro to be made in the development of bioenergy. It is then important to choose instruments that do not create needless uncertainties and costs, writes Tomas Kåberger at Lund University.

Birgitta Johansson, Editor

Birgitta Johansson is a scientific journalist and senior information officer at the Swedish Research Council Formas.

Internet addresses of Swedish universities and organizations mentioned in the book

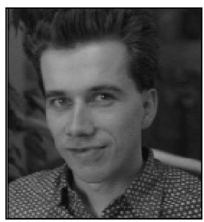
www.cbm.slu.se	Swedish Biodiversity Centre
www.chalmers.se	Chalmers University
www.elforsk.se	Elforsk AB, Swedish Electric Utilities' R&D Company
www.energimyndigheten.se	Swedish Energy Agency
www.formas.se	Swedish Research Council Formas
www.gu.se	Göteborg University
www.ivl.se	IVL Swedish Environmental Research Institute
www.lu.se	Lund University
www.miun.se	Mid-Sweden University
www.scb.se	Statistics Sweden
www.skogforsk.se	Skogforsk, Forestry Research Institute of Sweden
www.slu.se	Swedish University of Agricultural Sciences
www.sp.se	SP Technical Research Institute of Sweden
www.svebio.se	Svebio, Swedish Bioenergy Association
www.sweden.gov.se	Government Offices of Sweden
www.umu.se	Umeå University
www.vinnova.se	VINNOVA, Swedish Governmental Agency for Innovation Systems

Biomass – a scarce resource in the global perspective

The world now consumes around ten times more fossil energy than bioenergy. But the use of bioenergy is now increasing substantially. However, the global availability of bioenergy is insufficient to replace the fossil fuels, write three researchers at Chalmers University of Technology in Gothenburg. How should we use the scarce resources in the best possible way? And how can we restrict the possible negative effects of an increased demand for bioenergy? This concerns, for example, the exploitation of valuable ecosystems such as rainforests.

Göran Berndes, Physical Resource Theory, Chalmers University of Technology.

Julia Hansson, Physical Resource Theory, Chalmers University of Technology.



Stefan Wirsenius, Physical Resource Theory, Chalmers University of Technology.

This chapter deals with the amount of bioenergy that could possibly be used in the world in the future. Bioenergy has an obvious opportunity to play an important role in the energy systems of the future, but it will not suffice for all the various applications that may arise in the future.

Figure 1 shows how the global production of fossil fuels has grown since the early 19th century. By way of comparison, the world production of forest raw materials (wood fuels and industrial wood) is also shown, and so is the production of grain that accounts for more than half of the harvests from our fields. (We have recalculated all categories to a common unit to allow for comparison: biomass equivalents that correspond to around 5.5 megawatt-hours, MWh). The wood fuel consumption shown in the figure corresponds to the use reported by the UN Food and Agriculture Organization (FAO). The total use of biomass for energy is estimated to be more than double and also comprises, for instance, raw materials for biofuel production, such as maize and sugar cane, harvest residues, manure and the use of wood that is not recorded by the FAO.

An important conclusion that can be drawn from the figure is that the total production of fossil fuels – in addition to having grown and continuing to grow dramatically – is much higher than the production in agriculture and forestry. A condition for bioenergy being able to play an important role in the global energy transition is thus that we can increase very substantially the production of biomass for energy purposes. At the same time, the production of biomass in agriculture and forestry must increase substantially in coming decades in order to meet the need for food, paper, etc. for the growing world population.

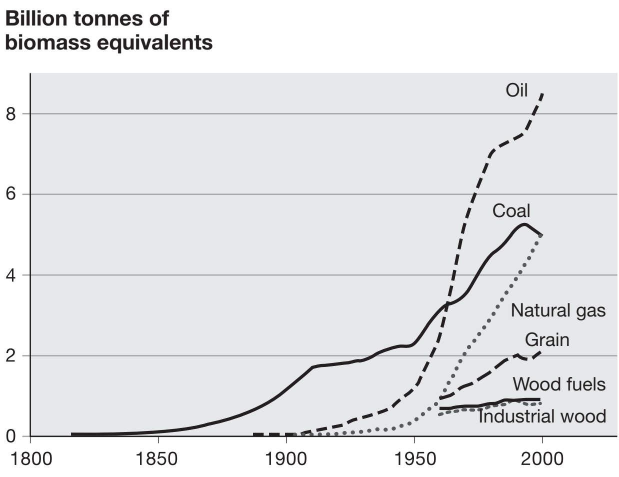


Figure 1. World production of fossil fuels and of products from agriculture and forestry. Industrial wood is the wood obtained from the forest for the production of paper, boards, chipboard, etc.

Bioenergy from agricultural residues

So how much bioenergy can we produce? And how will this be done? Our answer will begin with agriculture. Compared with the grain harvest shown in Figure 1, around 1.5 times as much harvest residues on the fields are generated every year. A substantial part of this could be used for energy purposes, but a great deal must also be left on the fields, since the harvest residues are needed for maintaining the fertility of agricultural land. If everything were taken, the risk of erosion and depletion of agricultural soils would increase substantially, and we would find it increasingly difficult to maintain the harvest levels in the long term. The harvest residues are also used for other applications, such as straw for livestock.

In addition to harvest residues, manure and food waste, for example, can be used for energy purposes. Figure 2 shows a number of bars that describe the results of a study at Chalmers of the global food system now and in the future. The bars reflect the magnitudes of some residual flows in the food sector that could be used for energy purposes – how they looked a little more than 10 years ago, and how they may look in 2030 for a number of different scenarios (see the figure text.)

It should be noted that the production of these residual flows will be much higher in 2030. This may appear self-evident, since the world's population is expected to grow rapidly – and thereby also the demand for agricultural products. But it is also clear that the primary production of crops and animal products could

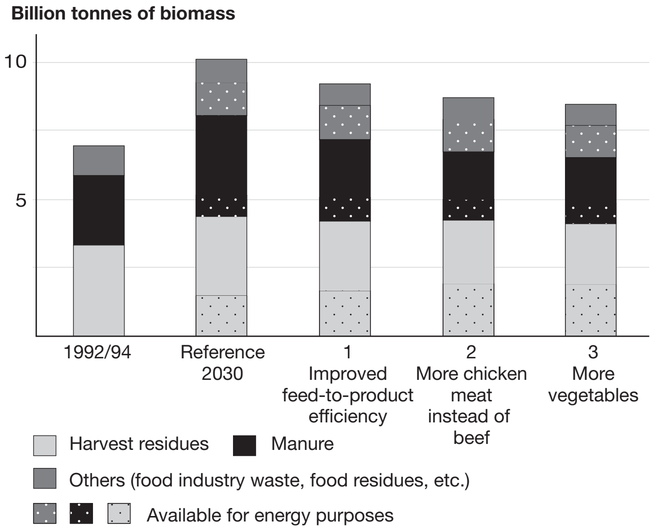


Figure 2. World production of residual products in the food sector, with possible use for energy purposes. The proportions that may be available for energy purposes are shown as "Available" and are dotted in the figure. In addition to the situation in 1992/94, the figure shows the conceivable situation in 2030 according to a forecast from the FAO (Reference 2030). Bars 1, 2 and 3 show the conceivable situation if developments deviate from the FAO forecast so that: 1) The productivity and the production of animal products (meat, milk, eggs) increases more rapidly than the value assumed by the FAO; 2) moreover, 20 percent of beef is replaced by pork and chicken meat; 3) in addition, the proportion of vegetables in our diet increases, i.e. the amount of meat decreases and the wastage of food in household and institutional kitchens decreases.

be substantially restricted and thereby the quantity of residues by increased feed-to-product efficiency in the production of animal products (less feed per quantity of meet, milk or eggs produced) and a change in diet. At the same time, a larger proportion of the residual products could then be used for energy purposes, since less residual products would be needed in the production of animal products. The available volumes of residual products roughly correspond to one sixth of today's global primary energy supply. The term primary energy denotes oil, coal, biomass, etc., before they are refined into commercial energy carriers, such as gasoline, electricity and pellets.

Bioenergy from energy crops on agricultural land

But the most important change is probably that less agricultural land (arable land and pasture) would be needed if we improved the efficiency of production of animal products and also decreased our consumption of animal products. The biomass intake via pasturage is roughly twice as high today as the global grain production shown in Figure 1, and the land used for pasture is more than twice as much as that used as arable land. The calculations in the study indicate that instead of an increase up to 2030 (from today's 5.1 billion hectares to around 5.4 billion in the reference case in Figure 2), we could reduce the agricultural land and could manage with 4.2–4.4 billion hectares (Figure 3).

This means that land is released, and some of it could be used for the production of energy crops. Assuming that 500 million hectares (which corresponds to roughly one third of the global arable land area) can be used

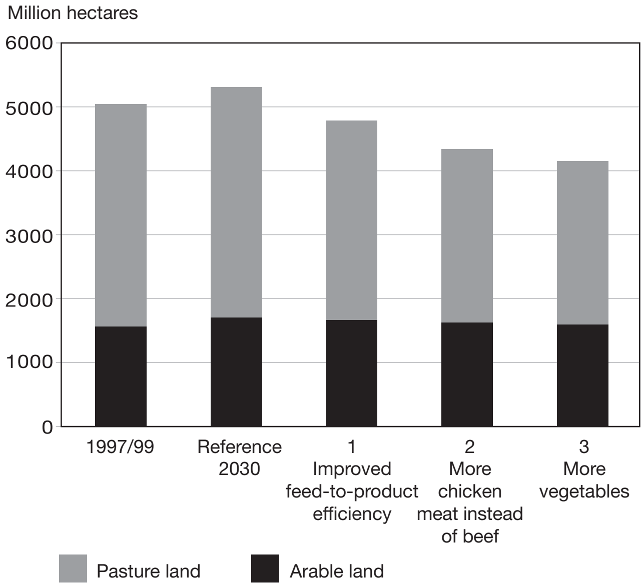


Figure 3. Use of agricultural land in the world in 1997/99 and 2030 for the same future scenarios as in Figure 2. Note that the area of arable land in the figure includes the use not only for food production, but also for crops such as cotton and natural rubber, and the production of grain, sugar plants, etc. that are used for the production of, among other things, industrial raw materials and fuels. This arable land area that is not used for food can roughly be estimated to be around 150 million hectares, i.e. almost 10 percent of all arable land.

and that we achieve an average harvest of 10 tonnes of dry biomass per hectare per year (corresponding to a good salix harvest in Sweden), we would obtain an amount of biomass corresponding to less than a quarter of today's global primary energy supply, or roughly the same amount as today's consumption of coal.

Bioenergy from forests and residues from the forestry industry

Residual products that can be used for energy purposes are also generated in the forestry sector. These include harvesting residues (branches and treetops, also known as logging residues or slash), and by-products from sawmills and pulp mills. But there are factors that partially restrict the use. Some of the logging residues may have to be left in the forest to sustain the fertility of the soil, and there are also competing uses of certain residual products for material production, such as for chipboard.

Figure 4 illustrates the conditions for bioenergy supply in forestry. The total energy supply in Sweden is around 450 terawatt-hours, TWh (excluding waste heat losses from nuclear power, which amount to around 150 TWh). Compared to this, industrial wood production in Sweden has an energy content of just under 180 TWh, as shown in Figure 4. Industrial wood is the wood extracted from the forest for the production of paper, board, plywood and so on. Assuming that it will be possible to utilize forestry residual products, including consumption waste from forest products (e.g. demolition timber) of the same order of magnitude as industrial wood production, forests can obviously account for a substantial part of Sweden's energy supply.

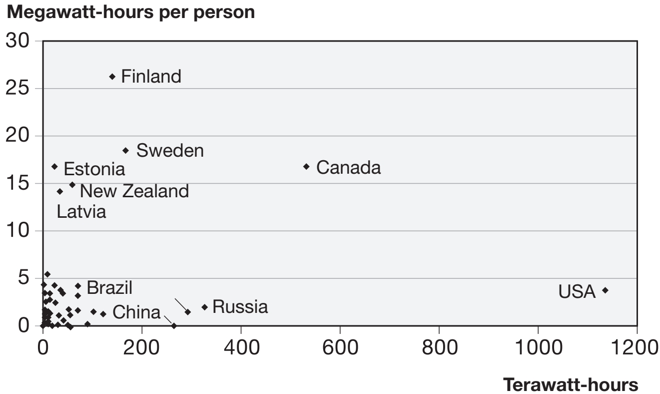


Figure 4. Industrial wood production in the world's countries, average for the years 2000 – 2003, converted to energy content. The figure shows the dominating industrial wood producers in the world and the per capita production in various countries. (Based on data from the FAO)

But the figure shows that the situation in Sweden is not representative for the remainder of the world, and is only representative for other countries that have a substantial forestry industry. Based on the same assumption, the global contribution of forests to the energy supply would be less than from agriculture. The energy content in today's global industrial wood production corresponds to only a few percent of today's global primary energy supply. Assuming that the industrial wood production is doubled during the coming decades due to population growth and the increasing use of forest products, contribution in the form of residual forest products would account for less than one tenth of today's primary energy supply.

Global contribution of bioenergy

Let us summate this. Residual products from agriculture could give a contribution that corresponds to one sixth of today's global primary energy supply, energy crops on agricultural land that is no longer needed for food production could perhaps account for one quarter, and the contribution from forestry could correspond to one tenth. The total contribution could thus be equivalent to just under half of today's global primary energy supply.

These are obviously rough estimates, and the most decisive factors can develop in very different directions, such as the land area that could possibly be used for the production of energy crops and the harvesting level that can be achieved. The possible future land area devoted to energy crops is largely dependent on the amount of land we will need for food production. As already shown in Figure 3, this depends on the type of food we choose to eat. The more vegetables we eat instead of meat, milk and eggs, the less land will be needed for food and the greater the area remaining for bioenergy. The same applies if we eat pork or chicken instead of beef or lamb. The possible land area used for energy crops will also be larger with increasing harvests per hectare from agricultural land, and with increasing efficiency of conversion of animal feed to meat, milk and eggs.

We may therefore face difficult choices if we are to increase the land area for bioenergy plantations to the extent outlined above. As an example, there are targets in Sweden and the EU for increasing the land area for ecological plant cultivation. The average harvest per hectare in ecological cultivation is lower than in conventional cultivation. This means that if the land area for ecological cultivation is increased, there will be less area for bioenergy plantations. To compensate for this, we could exploit land that was not previously used for agriculture or forestry, e.g. natural forests or other natural ecosystems. But this, in turn, could mean that the biological diversity would be reduced.

In order to increase the production of biomass for energy, food and industrial wood, the fundamental choice thus lies between either increasing the harvest per hectare, which could lead to significant emissions of, among others, over-fertilizing and toxic substances, or increasing the land area used, which could lead to loss of biological diversity. The best alternative is not self-evident, but many researchers lean towards it being better to increase the harvest per hectare, particularly as regards developments in tropical countries, in order to make it easier to protect the remaining tropical rainforests.

We have so far compared the possible future bioenergy potential with today's primary energy supply. But the energy consumption in the world is expected to rise substantially. We may perhaps hope that the global energy consumption during this century will no more than double, which presupposes much more efficient energy utilization than today, although many studies arrive at much higher increases than that. At the same time, a large part of the energy supply must take place without greenhouse gas emissions in the future if we are to achieve ambitious climate targets. The need for bioenergy and other climate-friendly alternatives will thus be very high.

Competition for biological raw materials and land may lead to higher prices

Bioenergy is the only one of today's renewable alternatives that naturally gives carbon-based fuels, on which large parts of the energy technology we have today are also based. This leads, for example, to bioenergy being relatively simple to use for replacing oil in the transport sector. Bioenergy is also a relatively inexpensive energy source compared to other climate-friendly alternatives, and the demand for bioenergy will probably be high also for electric power and heat generation. As a result, the risk is that there will be competition for biomass in the future, e.g. between a boiler station that generates heat for a district heating system and a factory that needs to use biomass for producing fuel for motor vehicles. This may lead to an increase in the prices of bioenergy.

There may also be competition for forest raw materials between the energy sector and the forestry industry, and for arable land (and water) between the energy sector and the food sector. High bioenergy prices may attract farmers to grow energy crops instead of food and animal feed crops, with the consequent risk of increases in the prices of food (and land). For ethanol and biodiesel, for example, farmers need not even change their crops, but simply sell the harvest to the user who pays the best price. We already note that grain prices, for example, are affected by an increase in demand for automotive biofuels – and this is taking place at a level at which the contribution from biofuels only accounts for a few percent of the world's total fuel supply for motor vehicles.

Calculations suggest that food and land prices may increase many-fold in the long term. But price increases are not, by definition, a problem – higher prices may be beneficial to third world farmers who will then enjoy higher incomes. And a growing bioenergy sector generates jobs, principally in rural areas. The Swedish forestry industry has expressed apprehension in the face of stiffening raw materials competition with the energy sector. This is because the forestry industry operates on an international market, and will obviously face a more difficult situation when Swedish initiatives push up the demand for biomass, if the forest raw material is not subjected to the same pressure in competing countries with a less ambitious climate policy.

No attractive green world around the corner

Perhaps the most important conclusion that can be drawn from this chapter is that we are not moving away from a world with a surplus of fossil fuels to an attractive green world in which we would be wallowing in bioenergy. A central question will be how we can use the scarce bioenergy resources in the best possible way. Regardless of where bioenergy will be used, the demand will probably increase robustly in coming decades. We will see good examples of how biomass production can take place in a way that provides environmental benefits other than merely a reduction in greenhouse gas emissions. But, we will very probably also see how the demand for bioenergy leads to the poor being displaced from their land, and how rainforests and other valuable ecosystems will be depleted or even totally destroyed in the search for bioenergy.

It is therefore important to establish systems (e.g. certification of automotive biofuels) that limit as far as possible the undesirable effects of the growing demand for bioenergy. It is also important to develop climate-friendly alternatives other than those based on biomass, e.g. for the transport sector. We will need to use a multitude of such alternatives in the future in addition to bioenergy. Finally, we must try to restrict our energy use – by efficiency improvements and by reflecting, to a greater extent than we do today, on how energy use is affected by our choice of everyday life.

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Bioenergy in Sweden

The term bioenergy means energy that is derived from biomass. All combustible biological material is a form of bioenergy. This may be wood, whole-tree chips, bark, chips, energy forest, energy crops, liquors from pulp production, domestic waste and industrial waste. In processed form, it may be an energy carrier such as, for example, electricity, heat, pellets, ethanol and biogas.

In Sweden, biomass fuels account for around 18 percent of all energy supply. Among countries in Europe, Sweden and Finland have the highest proportion of bioenergy in their energy systems. This is due to factors such as the two Nordic countries having abundant forestry and raw material resources, a well-developed forestry industry, extensive district heating systems and good transport facilities. In a global perspective, biomass are the most important fuel for a large proportion of the population in third-world countries.

The use of bioenergy in Sweden has gradually increased from just over 10 percent of the total energy supply in the 1980s to 18 percent in 2005. Industry and district heating plants accounted for most of the increase. The total energy supply in 2005 was 630 TWh or 493 TWh if the waste heat losses in nuclear power plants are disregarded (1 TWh or terawatt-hour = 1 billion kilowatt-hours). Also in 2005, 112 TWh of biomass fuels, peat and waste were used. The consumption was distributed onto various sectors as shown in Figure 1.

Most of the biomass fuels, peat and waste used in the Swedish energy system are domestically produced and consist of:

- wood fuels (wood, bark, chips and energy forest)
- black liquors and tall oil pitch (intermediate products and by-products of chemical pulp production)

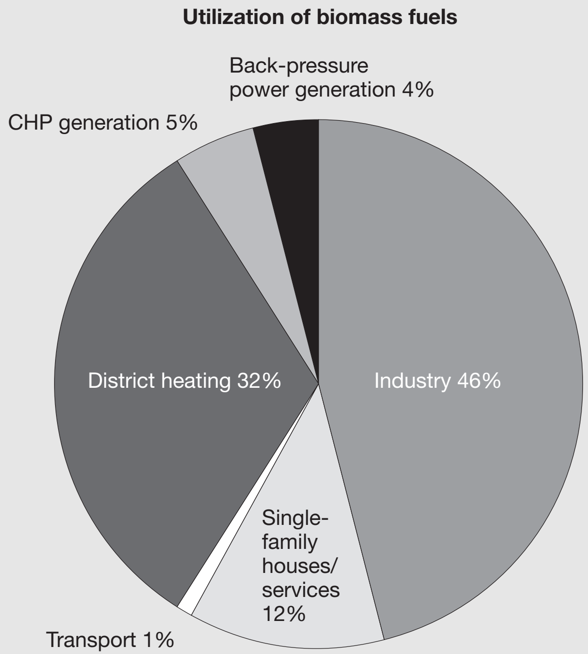

Figure 1. This is how the 112 TWh of biomass fuels, peat and waste were used in Sweden in 2005. (Source: Swedish Energy Agency)

- peat
- waste (from industrial plants and households)
- ethanol (in pure form for industry and as additive for 95-octane gasoline and as the main ingredient of E85 and E92 vehicle fuels)

Biofuels such as chips and wood are largely regional and local fuels, since the low weight per unit of volume and the low price limit the economically viable transport distances. (One cubic metre of oil is equivalent to 5–10 cubic metres of wood.) Biofuels are processed into pellets and briquettes in order to raise the energy density, facilitate handling and improve transport economy. In 2005, a total of almost 1.5 million tonnes of pellets, corresponding to around 7.2 TWh, were used in the Swedish energy system. Deliveries of pellets to the Swedish market have more than doubled between

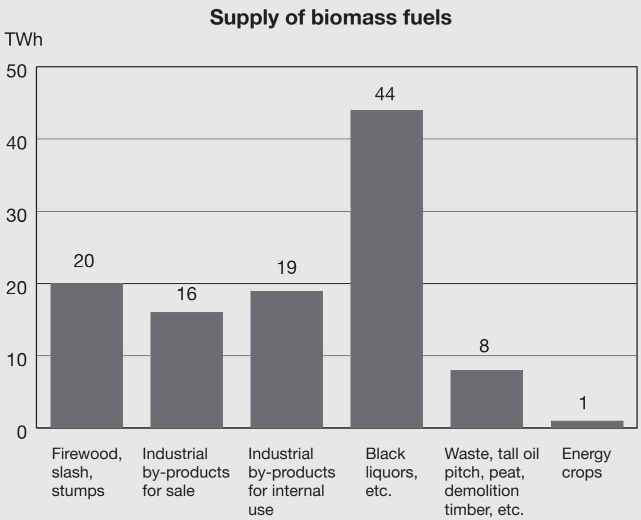

Figure2. Supply of biofmass fuels in Sweden in 2005. Fuels from agricultural land represent only 1 percent of the bioenergy in the Swedish energy system. (Source: Commission for Reducing Oil Dependence)

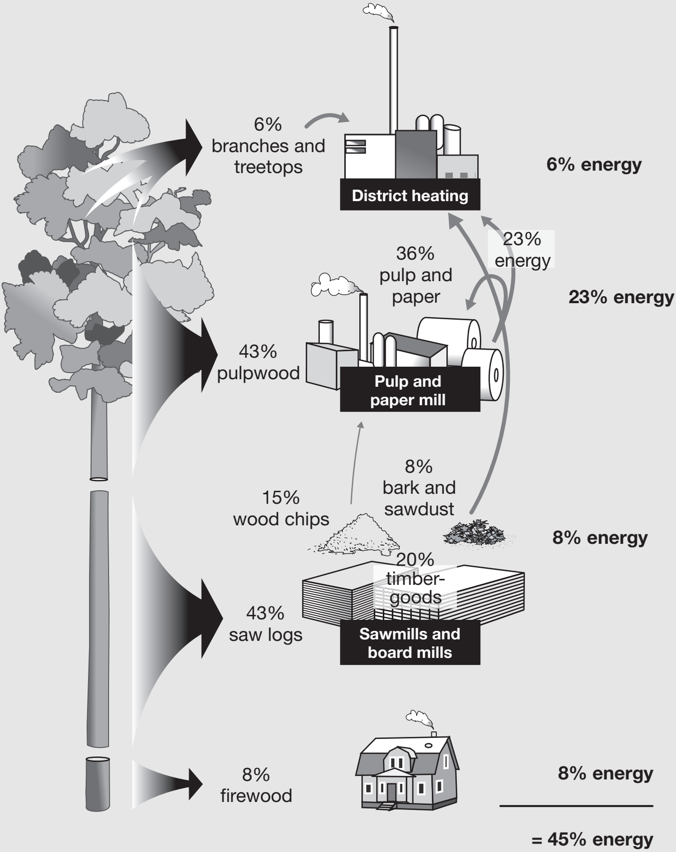

Figure 3. A large proportion of the annual felling in Swedish forests is already used for energy purposes. The figures show the situation in 2003, when 45 percent of the forest biomass was used for energy. But much more energy can be extracted from the forest. Around 20 percent of biomass in the form of branches and treetops are now left in the felled area, over and above the biomass shown in the figure. In addition, a further 20 – 25 percent of biomass are left in the form of tree stumps with root system (Sources: Forestry Industries, Statistics Sweden and Rolf Björheden, Forestry Research Institute of Sweden).

2000 and 2005. Significant quantities of biofuels, particularly ethanol and pellets, are also imported. Estimates indicate that the net import is between 5 and 9 TWh. It is estimated that 80 percent of the ethanol used as fuel is imported.

From biomass to end use

Biomass is of a variety of types (Figure 4). It may be rich in cellulose, in starch and sugar, or in oils. The term forest fuels means wood, bark and chips. Black liquors and tall oil pitch are by-products of chemical pulp production. Waste comes from households and industrial plants, and sludge comes from sewage treatment plants. Figure 4 shows how different types of biomass are subjected to various processes to convert them to energy carriers that can be used for different applications: heat, electricity and automotive fuel. As an example, ethanol is produced by fermenting plants that are rich in sugar and starch, or by hydrolysis and fermentation of dry cellulose-rich plants. Biogas is produced by methods such as digestion of wet biological material and waste.

A common feature of the first generation of automotive biofuels is that they are based on starch or sugar from annual crops. Cultivation consumes a certain amount of energy, and production in Sweden is restricted by the availability of land area. The technology is available today, and the work is done by yeast fungi. The second generation of automotive biofuels may be more diverse.

The common feature is that a system with better overall efficiency can hopefully be achieved by starting from wood and other lignocellulose than when starting from starch. The raw material base is large. The technology is in the course of development.

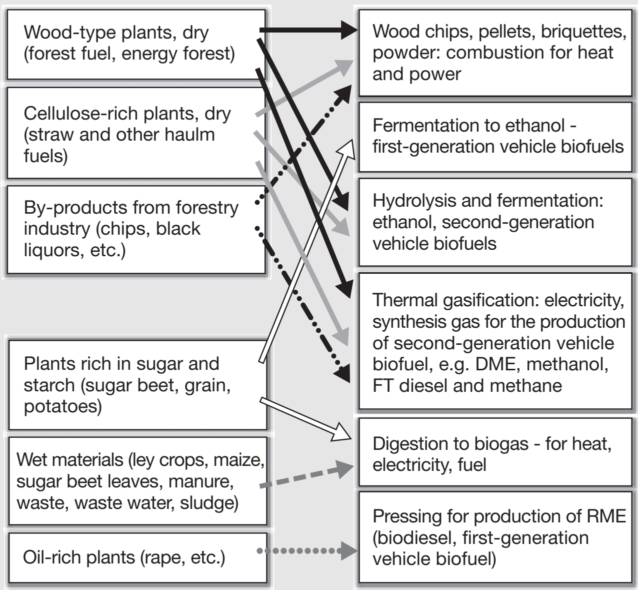

Figure 4. The figure shows how various types of biomass can be converted by various processes to different energy carriers that can be used for different applications.

Figure 5 shows the proportions of the end use in heat and power generation and automotive fuels that came from biomass fuels in 2002. The need for oil replacement is greatest on automotive fuels, although only about one percent of the consumption in this area is met by biofuels.

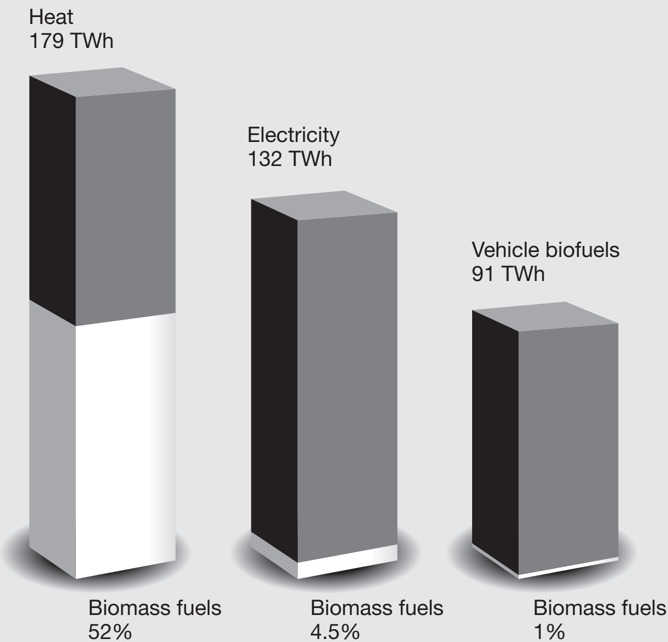

Figure 5. The proportion of biomass fuels in various applications in 2002: heat and electricity generation and automotive fuels. (Sources: Swedish Energy Agency and Swedish Bioenergy Association)

Forestry industry

In 2005, the industrial sector in Sweden used around 51 TWh of biomass fuels, peat, etc. for heat and electricity generation. The consumption was more than 7 TWh in the pulp and paper industry, and 5 TWh in sawmills and other wood products industry. Other industries used less than 1 TWh of biomass fuel. The energy from burning black liquor (that contains substances such as digester chemicals and lignin) is used internally in the chemical pulp industry and, in 2005, amounted to almost 38 TWh, excluding electricity generation. Tall oil and tall oil pitch are the by-products from the recovery of the digester chemicals. Both the pulp industry and sawmills use by-products such as sawdust and bark as fuels.

Single-family houses

During 2005, 11.2 TWh of biomass fuels were used for heating single-family houses in Sweden. Most of these fuels were firewood. A minor proportion consisted of chips, but the proportion of pellets and briquettes is growing. Wood firing is most common among home owners who have good access to forest. During the period between 2000 and 2005, the use of pellets in the single-family house sector has increased more than seven-fold, and more than 80 000 single-family houses were heated by pellet-fired boilers in 2005.

District heating stations

In 2005, more than 36 TWh of biomass fuels were used for generating heat for district heating (excluding electricity generation). Wood fuels accounted for more than 21 TWh, black liquors and tall oil pitch for more than 1 TWh, waste for more than 8 TWh, peat for less than 3 TWh, and other fuels for around 3 TWh. The use of wood fuels in the district heating sector has increased more than five-fold since 1990 (Figure 6). Wood fuels used were principally in the form of logging residues and by-products from the forestry industry. Processed fuels such as briquettes and pellets are being used to an increasing extent. Dumping of unsorted burnable waste is now banned, and waste incineration will probably continue to increase in coming years.

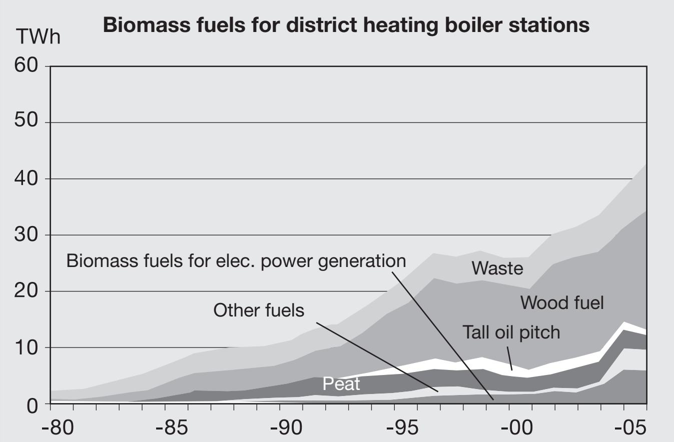

Figure 6. Consumption of biomass fuels, peat, etc. in Swedish district heating stations between 1980 and 2005. (Sources: Statistics Sweden and Swedish Energy Agency)

Peat, wood fuels and carbon dioxide

Wood fuels are regarded as "carbon dioxide neutral". The emissions of carbon dioxide from wood fuels are balanced by new vegetation absorbing carbon dioxide in a closed circuit and by the fact that logging residues left in the

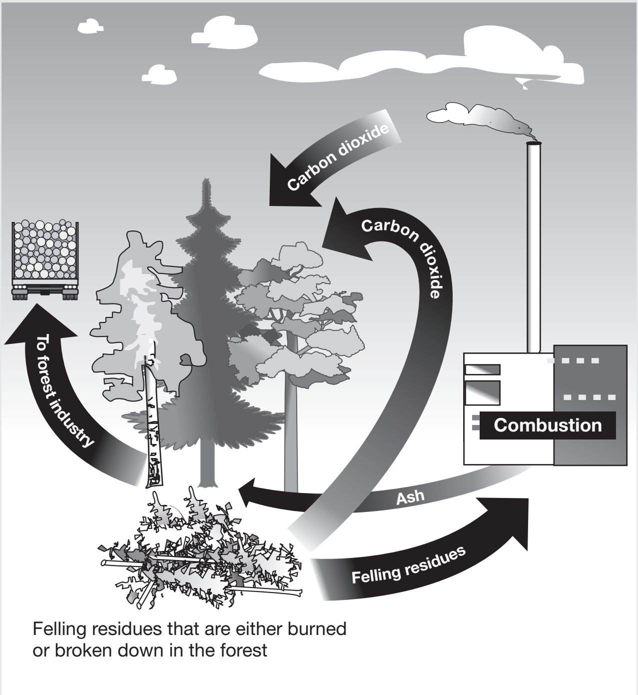

Figure 7. The carbon dioxide emitted when biomass fuels are burned is balanced by an equal amount of carbon dioxide absorbed by new trees or crops. The ash from combustion can be returned to the forest, so that the nutrient salts will also be recycled. If felling residues are left in the forest, they will still eventually decompose to carbon dioxide. This takes a much longer time than when the biomass is burned, but the difference will be very small in time.

forest would still decompose in time into carbon dioxide. The carbon dioxide emissions from biomass fuels are therefore considered to be zero (Figure 7).

The emissions from the combustion of peat are regarded as a net carbon dioxide addition to the atmosphere. There is thus a similarity with fossil fuels, even though peat is a much younger material. On the other hand, peat harvesting interrupts the flow of methane or carbon dioxide from the peat bogs. If this effect were credited to energy peat, the impact on the climate could be much lower in favourable cases than the impact from fossil fuels.

Peat has characteristics that are important when it is burned together with wood fuels. Peat reduces the risk of problems such as slag formation and corrosion in boilers. Since 1 April 2004, electricity generated with peat in combined heat and power (CHP) plants is entitled to electricity certificates. The EC Commission has approved peat as an efficient fuel for CHP generation for environmental reasons, and due to the fact that peat was likely to lose out in the competition with coal in CHP systems. On 1 January 2005, a common EU system was introduced for trading in emissions rights for carbon dioxide emissions. In this system, peat combustion is treated in the same way as burning fossil fuels. Whoever fires peat must obtain emission rights for the emission of carbon dioxide.

The text is based principally on the publication Energy in Sweden 2006 published by the Swedish Energy Agency. This is edited by Anna Lundborg at the Swedish Energy Agency.

Worth knowing

1 terawatt-hour (TWh) = 10^{12} watt-hours = 1 billion kilowatt-hours
1 gigawatt-hour (GWh) = 10^{9} watt-hours = 1 million kilowatt-hours
1 megawatt-hour (MWh) = 10^{6} watt-hours = 1000 kilowatt-hours

Focus on radical technology changes – not on bioenergy

Since bioenergy competes with food production, we do not believe that bioenergy is a realistic strategy for achieving long-term climate targets, write Ann-Kristin Bergquist and Magnus Lindmark. It is better to start now by focusing on the radical technical changes that will be necessary in the long term and devoting resources to them. Economic regulatory measures alone are not sufficient. Institutions are also needed in which the authorities and companies can draw up innovation strategies.

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When *Homo erectus* left Africa, biomass fuels were an essential condition for early human beings able to cope with the colder climates of other continents. During the 19th century, biomass fuels were still an important element in everyday life in Sweden. On the other hand, today's problems of global warming trace their roots to fossil fuels. What may be the most important aspect of the history of biomass fuels is therefore the history of how they were replaced by fossil fuels. Why this occurred and what consequences it had on the economy and society also demonstrate why global warming is such a fundamental problem.

The preceding history is long. The first steps towards global warming were taken in England in the days of Shakespeare and Elizabeth I. Even then, Englishmen used more coal than any other country, while the Dutch used vast quantities of peat. In both countries, economic growth was experienced although it was hardly discernible. The industrial revolution was still in the distant future. It was not until around 1830 that growth rate became sufficiently high to be noticeable during one lifetime. But the beginnings of the greatest economic and social changes since the agricultural revolution 10 000 years earlier were already there. There was no master plan for conversion to an industrial economy. The change took place in small or most imperceptible steps. And the core of the change was the transformation of society's energy system.

Energy system on the terms of photosynthesis

Ever since the dawn of humanity, all of society's energy supply was based on photosynthesis. Photosynthesis is the chemical process in which plants create hydrocarbons from carbon dioxide and water, using solar energy and chlorophyll. So it was plants that enabled solar energy to be transformed into energy forms that were usable in the economy. This relates to simple matters such as crops for food, feed for livestock and draught animals, and wood or charcoal for heating dwellings and for industrial processes such as the production of iron.

The availability of energy was a physical boundary for what could be achieved in terms of population growth and increase in industrial activities. As an example, the mechanical energy in the form of draught animals and human beings used in agriculture could never exceed the amount of energy obtained in the form of grain and feed. Admittedly, all energy used was not dependent on photosynthesis. Wind power had been propelling ships since ancient times and the use of windmills in Western Europe began back in the 12th century. In Holland, windmills were used mainly for pumping water in conjunction with drainage, which created new high-yield agricultural land. However, wind power and also water power (hydropower) used mainly for mills and in ironworks comprised a fairly insignificant part of the total energy consumption, which was dominated by fuels and food.

This also applies to shipping economies that were highly dependent on wind power, such as Holland and Norway.

It was extremely difficult to increase the energy flows to society. This is clearly due to the fact that plants need land area. As long as land area is limited, there is also a limit to the energy flows that humans can control. And since energy in the form of food was needed to meet the population growth and in the form of fuels for industrial plants, there was a trade-off situation between population growth on the one hand and industrial growth on the other.

Since industry, and particularly the production of iron, required large quantities of charcoal, every ironworks was dependent on a surrounding countryside on which forests were grown. Since energy was obtained from large areas of land, the industrial structure was also characterized by small units spread out over large areas. In an economy to which energy supply is dependent on photosynthesis, this was simply economically optimal. This obviously took place at the expense of small production volumes and high per-item costs. Since industry needed manpower and food supply needed land area, the population was also spread out across the countryside.

Coal took over

The major change came around 1720 when an iron-master in Derbyshire discovered that coal could be roasted to produce coke that could be used in blast furnaces. This new method was slow to spread. But it led in time to more iron being produced. And when the availability of iron increased, its prices fell. This, in turn, made it possible to produce more iron objects. At the same time, coal mines became deeper. On the rainy British Isles, this caused the major problem of mines filling with water. The pumps used for pumping out the water were originally driven by horses. But the combination of the need for water to be lifted from increasing depths and the rising cost of the oats for feeding the horses as a result of the growing shortage of land prompted the search for new technical solutions.

The answer lay in the Newcomen steam engine. This was so inefficient that it was profitable only at the biggest coal mines, where the fuel was literally on the ground around the engine. The steam engine was thus a highly specialized technology. But when it was developed during the latter half of the 18th century, it eventually revolutionized both the textile industry and the transport system.

Coal made more land available

Mine owners in Sweden also experimented with steam engines, but since Swedish steam engines were fired with wood, they were never profitable at that time. At the same time, coal became increasingly important in England. In England, the railways were preceded by canals, but the only canals that were profitable were actually those on which coal was transported. Out of the vast and famous British merchant navy, half of the tonnage was used for transporting coal from Newcastle to London. England had then definitely supplemented the photosynthesis-based energy system with a fossil energy system.

This can actually be illustrated by a simple worked example. We know the energy content (thermal energy per tonne or cubic metre) of both coal and wood. We also know how much coal was produced in England. We can then easily work out the amount of wood that would have been necessary if the thermal energy that came from coal had instead come from biomass fuels. Since the quantity of wood that can be used as fuel is limited in the long term by forest growth and since we know how many cubic metres of forest grew annually per hectare, we can also work out the land area that would have been equivalent to the English coal consumption. At the turn of 18th/19th century, the land area needed would have been as big as the total area of England and Wales. The conclusion is that coal saved land. This, in turn, had incredible effects.

Capital and fossil fuels went hand in hand

The industrial revolution was widely interpreted as a process in which capital in the form of machines, infrastructure and buildings replaced manpower. That is not wrong. The volume of capital per working hour (the capital intensity) is now very much higher than it was in the 18th century. The higher capital intensity has contributed substantially to the productivity (production per working hour) being much higher now than it was in the 18th century. The fact that productivity is high is the same as the real incomes being high. At the same time, the capital intensity aspect is not the whole truth.

Various studies have shown that the energy consumption increases roughly by almost as much as the amount of capital. Viewed historically, a 1 percent increase in real capital stock corresponds to around 0.8 percent increase in fossil fuel consumption. In simple terms, this is due to the fact that machines convert energy between different energy forms. An engine needs chemical energy in the form of fuel in order to develop kinetic energy, and furnaces need chemical energy to become hot. In economic terms, this means that capital and energy supplement one another. Pictorially expressed, a tractor needs diesel fuel to operate, while diesel fuel needs a tractor in order to perform a function and thereby have an economic value.

But if we tried to increase the amount of real capital (machines) in the photosynthesis-based economy, it would be very difficult to increase the energy flows to the same extent. The capital owner would realize that the extra production he can achieve from increasing the real capital decreases rapidly. This, rather than a shortage of capitalistic spirit, would prevent him from becoming a true industrialist. It was thus only when fossil energy sources enabled the energy flows to be drastically increased that the industrial revolution became possible. Given the technology at that time, it would not have been possible to build an industrial society on bioenergy.

Hydropower gave Sweden low electricity prices

One of the characteristics of Sweden is the low population density and large areas of forest. This, in turn, is a consequence of relatively poor conditions for agriculture. At the same time, the climate is not too harsh for forest growth, and the precipitation is abundant. Due to the latter, combined with the mountain chain, the country is endowed with several rivers. Even though Lule River in northern Sweden is not a patch on the Rhine, the volumes of flowing water and the heads available per inhabitant are exceptionally high in Sweden.

The decisive technology behind hydropower was the alternating current (AC) technology that became practically usable in the USA in the 1880s. The advantage compared to direct current (DC) was that the distances over which AC electricity could be transmitted with low energy losses were much longer. When AC technology was developed in the 1890s, Sweden became a country with exceptionally high opportunities for direct generation of electricity. The prices of electricity were therefore low compared to those in other countries, where the prices of electricity generally developed along the same lines as the prices of coal. Due to the low electricity prices, Swedish industry became more electricity-intensive. This applies not least to the metals industry, parts of the engineering industry, the chemical industry, and the pulp and paper industry.

Development of wood, coal, oil and electricity prices

The relative price is the price of a product compared to the price of another product. Let us consider the price of various energy carriers – coal, oil and electricity – compared to wood. Economic theories show that for products that are close substitutes, so that one product can be replaced by another, the prices on a free market will approach one another (converge). If the price development between two energy carriers begins to diverge from having been similar, this can be interpreted as the result of technical change or the fact that the market forms are different.

Figure 1 shows that the development of relative prices in Sweden during the period 1892–2000 is characterized principally by the substantial drop in electricity prices. This shows mainly that the prices of electricity were not decided on an international market and that the State through the Swedish State Power Board (Statens Vattenfallsverk) could administer the electricity prices as part of the industrial policy.

Price indices for coal, oil and electricity in relation to firewood

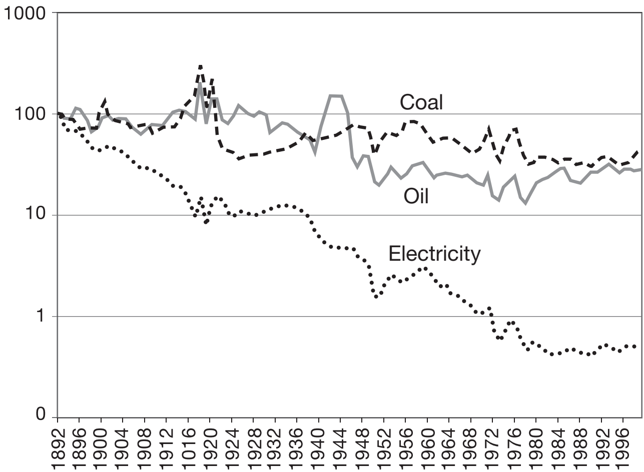

Figure 1. Price indices for coal, oil and electricity in relation to firewood in Sweden in 1892–1999 (index for 1892 = 100). The price series have been assembled from various historical sources. All price indices are expressed as the price of the relevant energy carrier divided by the price of firewood.

The relative prices of oil and coal were roughly unchanged up to the First World War. They developed along roughly the same lines as the prices of wood. The fuels were therefore close substitutes during the period. If the price of one fuel rose, the demand for another fuel increased until a new equilibrium price was achieved. But after the substantial fuel price increases after the First World War – which was a direct consequence of the war – the prices of both oil and coal dropped. While oil prices continued to drop, the prices of coal increased slowly. Around 1957, the relative price of coal was the same as in 1892. In the period between 1950 and 1973, the prices of oil and coal followed one another fairly closely. From the 1980s, the prices of all energy carriers developed in a similar manner.

The first problem is to determine why the prices of all three fuel types developed in different directions (diverged), above all in the inter-war period. They were no longer the same close substitutes as during the 19th century. At the same time, the development of the oil and coal prices displays a strong co-variation during the period between 1950 and 1973. They were thus close substitutes nevertheless, although this did not apply to wood. The explanations are that the change in the prices of oil and coal took place slowly on the international market. When oil became an increasingly important fuel for transport, high investments would have been needed on both the production and the consumption sides for the substitution between coal and oil to lead to price convergence. The fact that wood prices did not converge is probably due to wood of smaller sizes having become more important as input raw material for the pulp and paper industry. This expanded not least during the inter-war period, which was made possible by factors such as low electricity prices. Figure 2 also shows that the prices of oil after the inter-war period largely followed price developments in the pulp and paper industry. Due to the inexpensive electricity, wood was more useful as raw material than as fuel.

The second problem is why the relative prices again appeared to follow one another after the 1980s. An

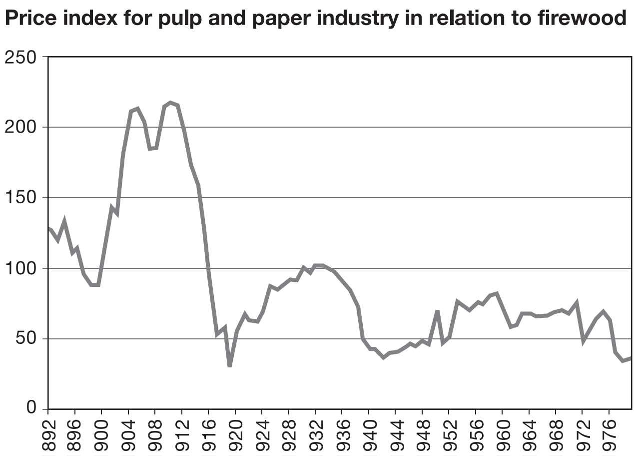

Figure 2. Price index for pulp and paper industry in relation to firewood prices between 1892 and 1980 (index in 1930 = 100). The price index is thus calculated as the price of the pulp and paper industry products divided by the price of firewood.

explanation is that the direct-generated electricity had by then been expanded to the capacity that society could accept as regards factors such as nature conservation. More electricity is thus being imported from coal-fired power stations, for instance. In addition, the price development suggests that wood has gained increased importance in recent years as energy carrier, e.g. as fuel for combined heat and power (CHP) stations.

Fossil energy for economic growth

The most important lesson from the history of biomass fuels is how they have been replaced by fossil fuels, which was a prerequisite for the industrial revolution and for long-term economic growth. The reason was that the supply of energy could be released from the need for land area. At the same time, fossil fuels are a finite resource, which worried the British political economist Stanley Jevons in the 1880s. But when the energy flows could thereby increase in a way that was inconceivable up to that time, conditions were created for large-scale industrial plants, large cities, regional and international work sharing, and so on. At the same time, air pollutants in cities increased alarmingly, also as measured by the yardsticks of their time. Today, few economists regard, just like Jevons, the growing shortage of fossil fuels as the most serious threat to welfare. The limiting factor is instead the ability of the atmosphere to absorb carbon dioxide without the climate being affected.

The yield of agriculture was also affected by the increasing mechanization and later by the use of artificial fertilizers, both of which were related to the new energy system. The 18th century economists had no conception of economic growth of the type we have experienced from the period between 1830 and today. When Adam Smith (1723–1790) advocated the possibility of England increasing its welfare by free markets, the famous "invisible hand", and work sharing, he envisaged how England could pull itself up to the income levels that the 18th century Dutchmen enjoyed. The reason was also that the economic thinking was trapped in the realities of the photosynthesis-based economy.

Today's challenge

Today's challenge to create a highly productive economy that is independent of fossil fuels and nuclear power is comparable to achieving a transformation of the same magnitude as that in the industrial revolution. The difference is that the intention is to achieve this by various types of political regulatory instruments. The industrial revolution was not created by political measures aimed at industrialization. On the contrary, it was at least a century-long process driven by the small decisions of a multitude of individual players. The climate issue demands a transformation within a shorter space of time. If the transformation is based on fossil fuels being replaced by biomass fuels, society will again be forced to draw a balance between food production and bio-energy.

We therefore do not believe that bioenergy is a realistic strategy for achieving long-term climate targets. It would be better to begin now to focus on and allocate resources to the radical technical changes that will be necessary in the longer term. Historical studies of technical change show that environments that are open to experimentation, failures and long-term strategies achieve innovations. Historical studies also underscore the fact that the choice of technology by companies often involves the choice between technical development tracks and not between ready-made technical solutions the costs of which are known. Since technical development is a very uncertain process, companies tend to choose conservative solutions, and this is one of the reasons why fundamental technical changes are so difficult to achieve.

Historical experience of technical development also shows that changes in prices are only one of the many driving forces and conditions for technical change. We therefore believe that society cannot rely only on economic regulatory instruments. These are good for achieving efficient choice between known technical solutions, but if conditions are to be created for long-term technical change, institutions are also necessary in which the authorities and companies can draw up innovation strategies. Environmental adaptation of Swedish industry during the period between 1970 and 1990 took place largely in this manner, and we believe that the experience from this period should also be put to use in the climate policy.

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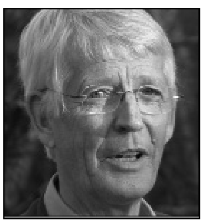
Magnus Lindmark is Associate Professor at the same institution and is working on matters related to long-term relationships between the environment and economic growth.

Biomass in Sweden – a vast but still insufficient resource

The forest in Sweden will always be a much greater source of bioenergy than arable land. But however much we endeavour to increase the production of bioenergy from agriculture and forestry using traditional methods, the availability within a century will still be unable to meet the demand. If the biological potential of the forest is to be put to full use, rules and attitudes must be changed in matters such as fertilization, clonal forestry and foreign tree species, write Pål Börjesson, Sune Linder and Tomas Lundmark.

Pål Börjesson, Environmental and Energy Systems, Lund Technical University



Sune Linder, Institution for Southern Swedish Forest Science, Swedish University of Agricultural Sciences

Tomas Lundmark, Department of Forest Ecology and Management, Swedish University of Agricultural Sciences

Opinions are divided on how much biomass fuels agriculture and forestry in Sweden will be able to produce in the future. Some claim that agriculture could never produce more than merely a fraction of what forests can produce, whereas others claim that the biofuel potential of agriculture is large. Different assessments are made of what may be profitable to do in order to increase the production of biological raw material, and views differ on what society and politicians may allow in the future. Growing biological raw material on agricultural land is greatly affected by a policy of extensive support system for agriculture, whereas production in the forest is pursued on commercial grounds. This does not make the future easier to predict.

On agricultural land, we have long used a cultivation system based on improved plant material, intensive cultivation practices, fertilization and chemical pesticides. This means that growth on agricultural land is close to what is biologically possible. On the other hand, cultivation on forest land is extensively pursued almost exclusively without the supply of nutrients and pesticides. The forest as a resource for producing biological raw material is therefore still far from its full potential, since the availability of nutrients in the soil – mainly nitrogen – is the growth factor that places the greatest limitation on biomass production in our northern forest ecosystem. This is important to remember when discussing how much the forest can produce.

How much bioenergy agriculture may produce in the future is dependent on many different factors, e.g. how the agricultural policy support system will develop, what energy crops we choose to grow, where in Sweden the plantations will be located, what type of agricultural land we put to use, and how much residual products from plant cultivation and livestock production will be used for energy production. This, in turn, is dependent on how profitable it is for the farmer to produce bioenergy. Similarly, forest management is guided by economic choices within the framework set by what is politically permissible and biologically possible.

More residual products from agriculture

Today's Swedish agricultural land has an area of less than 2.7 million hectares and produces annually around 80 TWh of biomass. Out of this, 30 TWh consist of residual products that are harvested only to a minor extent, such as straw. More than 40 percent of agricultural land are used for meadowland (grass for animal feed), just under 40 percent for growing grain, less than 10 percent for other cultivation (oil-yielding plants, sugar beet, potatoes, energy forest, etc.) and 12 percent are left fallow. From the resource viewpoint, we should increase the use of existing residual products for energy purposes. It is estimated that we could increase the use of straw for energy purposes by up to around 6 TWh annually, without any negative ecological consequences. In addition, we could theoretically obtain between 4 and 6 TWh of biogas from the manure from today's livestock production. From sugar beet tops and leaves, we could produce just under 1 TWh of biogas. Together with these 10 TWh of bioenergy from existing residual products, agriculture could then deliver bioenergy in the form of energy crops.

The available land area for forest production is 22.2 million hectares, which is more than eight times greater than the agricultural land area, and the annual growth of stemwood in the forest corresponds to about 250 TWh annually. By far the greatest part of today's use of biofuels in Sweden – more than 100 TWh annually – originates from the forest, in which the major part consists of residual products from the forestry industry. The contribution of agriculture is only about 1 TWh.

Poor profitability on fallow land

The view is often expressed that, in order to avoid competition with food production, we should use land that lies fallow for growing energy crops. Out of the 12 percent of Swedish arable land that is fallow today, almost half (5 percent of the arable land) is mandatory fallow land on which today's agricultural policy demands that we should not produce food, in order to reduce surplus production. In addition, about 7 percent of the arable land is voluntarily left fallow because of poor profitability. Arable land that is left fallow is usually poorer and less profitable to cultivate than average agricultural land. As a result, the biomass fuel potential of this land will also be lower. The proportion of land that is voluntarily left fallow is highest in central Sweden, where the harvest levels are around 30 percent lower than in southern Sweden.

If we were to grow ordinary agricultural crops such as grain and oil-yielding plants for energy production on today's fallow land, we could produce around 5 TWh of bioenergy annually. But one problem is that the profitability of this inferior land is also poor for energy crops. Some form of economic support would probably be necessary for getting energy production going on this land.

Different crops give different yields

The amount of energy we can obtain per hectare differs widely between different crops. If high-yielding energy crops are grown, such as energy forest (willow, poplar, hybrid aspen) and sugar beet in southern Sweden, the energy yield is roughly twice as high as rape seed cultivation, and around 50 percent more than when we grow grain. If straw is also taken into account, the differences will be somewhat lower.

Mainly grain and rape seed are grown today as energy crops, and then as raw material for vehicle biofuel (ethanol and rape methyl ester, RME, respectively). These two energy crops are the most profitable for the farmer today. Only around 0.5 percent of the arable land is used for growing energy forest (willow), which is then used for heat generation in district heating plants. To increase the energy forest cultivation, profitability must be improved for the farmer by increased demand and higher price, or by special support for developing the market. If fallow land were put to use for growing high-yielding energy crops, bioenergy production could rise to between 7 and 8 TWh annually.

Agricultural scenarios for 2020

Around 6 percent of the Swedish agricultural land are used today for growing grain that is exported and commands world market prices that are often low. But farmers are compensated for this. In addition, more meadowland is cultivated than that needed for animal feed at today's level of livestock production. These two types of "surplus production" could be replaced by energy plantations, without competing with the cultivation of food crops for our domestic consumption.

If we used 20 percent of today's agricultural land for growing mixed energy crops (both low-yielding and high-yielding) on parts of today's fallow land and surplus land for grain and meadowland, we would be able to produce around 15 TWh of bioenergy (Figure 1). By plant improvement and improved cultivation techniques, we would be able to produce around 20 TWh by around the year 2020 on the same land area. By plant improvement and improved cultivation techniques, we would also be able to achieve higher harvests of ordinary foods and animal feed crops. If the need for these crops were constant, we could release a further 10 percent or so of agricultural land for bioenergy production by 2020, and then produce a total of around 30 TWh on 30 percent of agricultural land. Further on in time, genetically modified crops could lead to even higher harvest increases. On the other hand, an increase in ecological cultivation may reduce the access to agricultural land for bioenergy production. The harvest levels from ecological cultivation are often around 30 to 40 percent lower than from conventional cultivation.

Uncertainty concerning marginal agricultural land

Views are often advanced in today's debate concerning marginal, former agricultural land also being used for energy crop production in the future. But there is great uncertainty concerning the availability of this marginal agricultural land for energy crop production and the productivity of such land that is not used today. Estimates show that between 100 000 and 400 000 hectares of marginal arable land is available for bioenergy production. Poor profitability is probably one reason for this land not being used today, not even for forest production. Economic support would be needed to start large-scale cultivation of this land.

Part of this land is also valuable for retaining in order to conserve biological diversity in the forest and agricultural landscape. Farmers already receive financial compensation for part of the old pasture land and

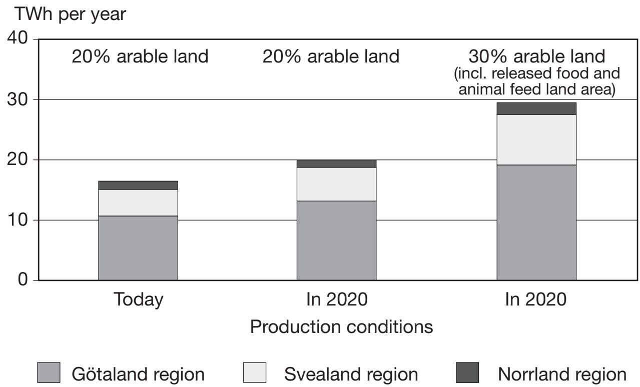


Figure 1. Gross production of bioenergy if 20 percent of today's agricultural land area is used for cultivation of energy crops using today's production conditions, and using expected production conditions in 2020. Increased harvests due to plant breeding and improved cultivation techniques are estimated to be able to release a further 10 percent of agricultural land by 2020 if the need for domestically produced food and animal feed crops is constant and these crops are produced using conventional methods (bar to the left). The energy crops are assumed to be a mixture of low-yielding and high-yielding crops.

fenced fields. A rough estimate of the significance that marginal, former agricultural land may have for future production of bioenergy is shown in Figure 2, assuming that the production of bioenergy on this land may vary from just over 1.5 TWh up to more than 7.5 TWh annually. Marginal agricultural land is estimated to consist largely of small, irregular fields, on which fast-growing deciduous trees such as poplar and hybrid aspen, together with Norway spruce would be best suited for growing. Traditional forestry machines could be used.

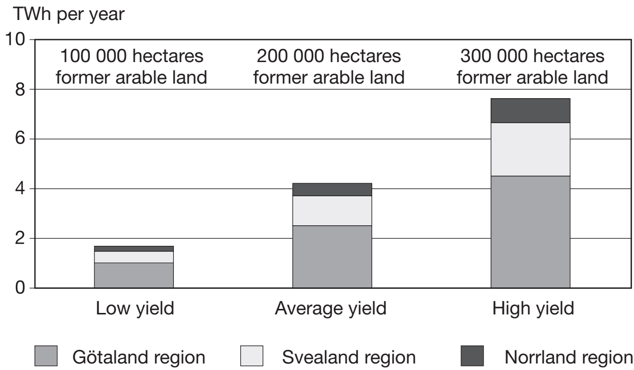


Figure 2. Dependence of gross production of bioenergy on marginal, former agricultural land on the available land area and the harvest yield. The energy crops on this land would probably largely consist of fast-growing deciduous trees such as poplar and hybrid aspen, as well as Norway spruce. "Low yield" corresponds to the productivity on somewhat poorer forest land in the region, "average yield" corresponds to average forest land, and "high yield" corresponds to better forest land.

Politics set the limit for forest growth

In order to maximize the production of biomass from a certain area of forest, the tree species selected must be right, the stand must have a closed canopy, and the availability of nutrients must be good. Modern nutrient optimization trials, with the support of 80 years of plant-nutrient research in Sweden, have shown that it is possible to achieve very high production by supply of plant nutrients according to demand. Volume production of Norway spruce can be doubled in this manner in parts of southern Sweden, and can be increased more than three-fold in northern Sweden. With the same input on forest land as that which is standard on agricultural land, the production levels would thus be similar. But to maximize production from the forest, the economic and political conditions must then be right. In practical forestry, it would therefore not be unrealistic to assume that the annual growth, viewed over a whole rotation period, could be increased by at least 5 cubic metres per hectare in the whole of the country, except on the most fertile land.

At the present time, it is not the biological production potential of forest trees that set the limit for the amount of forest raw material that could be produced, but it is the economic and political restrictions. The current forest policy does not allow for silviculture systems involving repeated and optimized fertilization that leads to a substantial increase in average growth during the rotation period. For environmental reasons, drainage of new marshland is not allowed. But from the research viewpoint, it is important to continue to study various aspects of production-optimized forestry, not least from the environmental aspects. Regardless of the opinion concerning intensive cultivation of forests, knowledge must be acquired to enable the right decisions to be taken.

The forest in different time perspectives

Assuming that the production levels achieved on forest land can be equivalent to those achieved on arable land, the potential for producing biological raw material in the forest could be three to four times higher than it is today, i.e. between 600 and 800 TWh in energy terms. In practice, these are obviously not realistic levels, although there is still a great deal of raw material available from the forest in the short and long terms. The first and quickest way of increasing the yield of energy raw materials from the forest is to harvest more of the forest that is felled. By putting to use more of the branches, treetops, stumps, and small stems, an extra harvest of the order of 40 TWh (equivalent to around 40 percent of today's gross availability) could be obtained without any major modifications to the forestry now pursued. This extra raw material is already available today.

Future measures that increase the possible harvest of forest would mean that the quantity of slash (branches and treetops) and stumps that could be harvested would increase correspondingly. On marshland with peat that has already been harvested, scope is available for increasing the growth quickly by ditch clearance and fertilization (including the spreading of wood ash). For the country as whole, the addition is estimated to be 4 TWh annually. Relatively high growth increases of the order of 40 TWh could be obtained in the long term by better regeneration, and improved plant and seed materials. By increasing the land area planted with lodgepole pine instead of Scots pine and by reverting to the 1980s level of fertilization of forest land late in the rotation period, a further 15 TWh could be obtained every year.

If we also assumed that the Prime Minister's Oil Commission is right in its opinion that the fertilization of 5 percent of the forest land is optimized before 2020 by repeated fertilization from the young forest stage, at least a further 10 TWh could be added to the calculation. The one single measure that produces the highest effect is fertilization of young forests. Assuming nutrient optimization on all of the land considered suitable in today's perspective regarding factors such as tree species (Norway spruce), fertility of the soil and nature conservation considerations, it is estimated that around 3.3 million hectares would be usable. This could produce an annual increase in growth corresponding to 35 TWh.

Forecast for 2100

The contribution of the forest to the energy supply of the country could probably be more than doubled during the 21st century from around 100 TWh today to a little over 200 TWh in 2100 if the measures described really are implemented. How the demand for bioenergy will develop by 2100 and how agriculture and forestry will be capable of meeting the needs is shown in Figure 3. It is assumed in the calculations that the demand will continue to develop as it has done during the past 15 years, i.e. will increase by around 2.5 TWh annually.

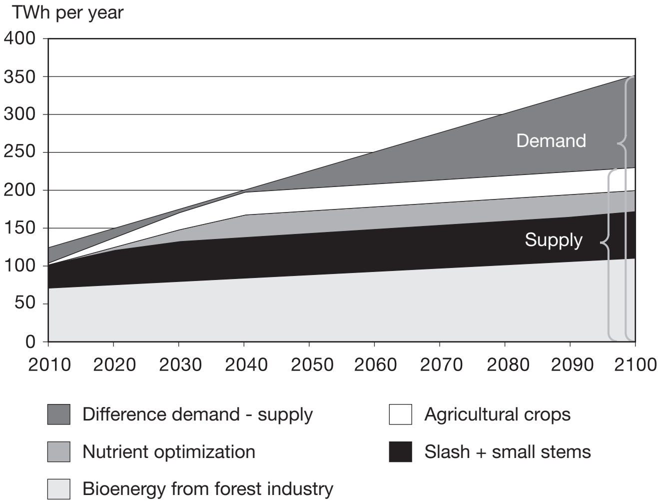


Figure 3. Expected development of demand for bioenergy in relation to the ability of forestry and agriculture to meet the demand up to 2100. The demand will be much higher than the supply, in spite of a number of measures in agriculture and forestry. This does not include genetically modified plants, more extensive fertilization or growing of foreign tree species on a large scale. Neither are the effects of climate change included in the calculations. The forest will continue to be the biggest raw material base for bioenergy in Sweden.

Better regeneration, improved seed and plant materials, more lodgepole pine, increased "traditional" fertilization, nutrient optimization on 5 percent of the land area, ditch clearance, and planting of fields with Norway spruce and poplar are expected together to be able to produce a growth increase of 40 percent or 40 million cubic metres. The full effect would be achieved after a rotation period of around 90 years. In this calculation, all round wood would go to traditional forestry industry, which would result in the amount of bioenergy from the residual products of the forestry industry increasing in time. Branches and treetops, stumps and small stems that can be harvested increase proportionally with the increased felling. In addition to the Swedish Oil Commission proposal for nutrient optimization of 5 percent of the forest land, i.e. around 1 million hectares, all suitable land with the present tree species distribution and structure would be used, i.e. an additional 2.3 million hectares, would be used for energy production. The adjustment would take place at the rate of 1 percent of the total land area annually, i.e. around 200 000 hectares per year. At full effect, this would give a further 25 TWh.

In Figure 3, arable land gives 5 TWh as residual products from today's farming, and a growing proportion of the arable land, including fallow land, is changed to energy cultivation that corresponds to around 20 percent of the total arable land area by 2040. The energy crops would initially be mainly one-year, but increasing amount of high-yielding perennial crops would be grown to produce a total of 30 TWh annually during the whole of the period.

The various measures for increasing growth have different delivery times, and the possible extraction of extra biological raw material from the forest will therefore take place in stages. Summating all "probable" yields that the forest contributes to energy supply, we reach a figure that is roughly twice as high as today's level. Assuming that most of the extra growth that is harvested is used for sawn goods and pulp production, the equivalent of 40 million extra cubic metres would go to expansion of the traditional forestry industry. But this does not mean that the possible increase in energy supply will disappear. Out of the raw material that goes to the forestry industry, around half will be residual products that can be put to use as energy. In this scenario, the space available for the expansion of the energy sector based on forest raw materials would still be significant (Figure 3).

Forest is the biggest bioenergy source

The total annual biomass production on today's agricultural land corresponds to around 30–40 percent of today's forest production, while the arable land area is about one eighth of the forest land area. Only a marginal part of the agricultural biomass is used today for energy purposes, and the magnitude of the biomass fuel potential in the future largely depends on how much agricultural land is used for energy crops, what energy crops are grown, and the proportion of the existing residual products that is put to use. This, in turn, is decided by the economic conditions for the farmer to produce bioenergy in competition with food and animal feed crops, where agricultural policy support systems, energy price levels, etc. are decisive.

Even if ambitious political regulatory instruments promote a substantial increase in bioenergy production in agriculture, the forest will always remain the biggest raw material base for bioenergy in Sweden.

The annual wood production in Sweden is more than 100 million cubic metres today and will remain at this level if future forestry is run as it is today. The consequence of such forest management is that it will be unable to meet the raw material needs of both the forestry industry and the rapidly expanding needs of the bioenergy sector. In the coming few decades, we will be unable to increase the availability of forest raw materials by improved and/or genetically modified trees, and we will have to rely on the production of existing forests.

Swedish forests fortunately already have the biological production potential that could safeguard the needs of both industry and the energy sector. But to achieve and put to full use this biological production potential, regulations and attitudes must be changed as regards measures such as nutrient supply, clonal forestry and foreign tree species, and the development of silviculture methods that include forest fuels as an ordinary assortment in sustainable forestry. There are thus no limitations in the ability of the forest to contribute to successful climate work, and it is rather our own inability to see the opportunities offered by the forest. If we begin to see these opportunities in forestry and also in agriculture, biofuel may again become the dominating source of energy in the Swedish energy system within a few decades, as it was at the beginning of the 20th century.

"Minds are like parachutes – they work best when open."

Pål Börjesson is Associate Professor of Environmental and Energy Systems at Lund Technical University. His research is focused on broad, inter-disciplinary system studies of bioenergy systems, with focus on how these can be put to use in the best way, taking into account the environment, energy, resources and costs.

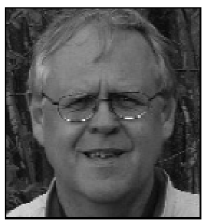
Sune Linder is Professor of Forest Ecology at the Swedish University of Agricultural Sciences and researches principally into the dynamics of carbon and nutrients of the forest ecosystems in relation to silviculture methods and climate changes.

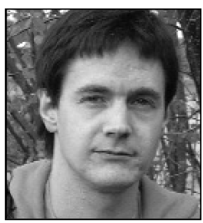
Tomas Lundmark is Professor of Silviculture at the Swedish University of Agricultural Sciences. He conducts research on alternative forest management practices which can meet the increasing demand for raw material from the forest.

International travels of biomass fuels

Trade in biomass fuels is likely to increase in the future. Our bioenergy imports into Sweden are so far higher than our exports. But this may change as the demand in other countries increases. Provided that biomass fuels are produced and transported in a sustainable manner, they will be one of the most important tools for coming to grips with the energy and environmental problems of the 21st century, write Bengt Hillring and Olle Olsson at the Swedish University of Agricultural Sciences.

Bengt Hillring, Department of Bioenergy, Swedish University of Agricultural Sciences





Olle Olsson, Department of Bioenergy, Swedish University of Agricultural Sciences

As recently as the beginning of the 20th century, bioenergy met almost half of the world's energy consumption. But not until the 1950s did we begin to use more oil than bioenergy, and even today, bioenergy is by far the most important energy source in many of the world's developing countries. However bioenergy acquired a new role in recent decades, particularly in densely forested countries such as Sweden, Finland and Austria. In pace with our endeavours to cut down on the consumption of fossil fuels for environmental and cost reasons, bioenergy is increasingly emerging as a large-scale and commercially viable energy source.

However, due to the spiralling prices of oil and the increasing awareness out in the world of how our emissions affect the global climate, interest in bioenergy is growing also in countries that have limited domestic forest resources. What is now happening is that, in the first place, countries all over the world are studying all possibilities of putting to use their domestic resources for the production of biomass fuels. These include olive residues in Greece, grape residues in France, and branches and treetops from Swedish forests. In the second place, we will see a high increase in international trade in biomass fuels.

Standardization in progress

Densely populated countries that have no major domestic resources, such as the Netherlands and Belgium, are working hard on establishing international trade in biomass fuels. As an example, the Dutch have the ambition that the port of Rotterdam should become a sort of hub for trade in biomass fuels in the same way as it is now a hub for oil on its way to continental Europe. The Netherlands has already set off the import of large quantities of pellets from Canada and the countries around the Baltic Sea. Pellets are fired together with coal in condensing power stations in order to reduce the emissions of greenhouse gases. Pellets are also shipped from Rotterdam by barges out on the rivers of Europe.

But in spite of these initiatives and the keen interest in bioenergy, trade in biomass fuel has not yet taken off. A contributory reason is the lack of uniform standardization. There is simply no general agreement on the definition of what properties pellets, for example, should have. Such a standard is in the course of preparation, but it is expected to take a long time before it is established. So it is difficult for buyers to be certain of the properties of the product they buy. Trade in biomass fuels is therefore so far mainly taken place on the basis of long contracts between buyers and sellers who have been able to build up confidence and thus safeguarded quality.

Sustainable biomass fuel production?

If trade in biomass fuels is to become a strong and sustainable long-term activity, it is also important that the fuel marketed is produced in a sustainable and environmentally friendly way. The biomass extracted must be replaced by some new growing biomass if the energy obtained from the fuel is to be regarded as renewable and carbon dioxide neutral. To be a little cynical, this is also a matter upholding the image of bioenergy as being an environmentally friendly energy source, which is a problem that the Dutch energy producers have experienced in recent years.

One of the large Dutch energy companies previously used large quantities of Indonesian palm oil as fuel. In many cases, large-scale production takes place in an environmentally very dubious manner. Large tracts of natural forest are felled in order to make room for oil palm plantations, and in pace with the disappearance of natural forests, many sensitive animal and plant species are threatened with extinction. When this became widely known in the Netherlands, it caused a storm of protests. Demands were raised that the use of palm oil as fuel should cease, which is what happened. The energy company involved has now drawn up a programme that guarantees that production of all biomass fuel used will take place in a sustainable and environmentally friendly manner.

Has Sweden become Europe's rubbish dump?

A debate in many Swedish local newspapers has taken up a subject that many consider to be strange, namely that Sweden is importing various forms of waste from other parts of Europe. This was ordinary mixed domestic waste and also a large amount of chipped wood waste. During the last decade, Swedish energy producers have imported relatively large quantities of recycled wood fuel from countries on the Continent, principally Germany and the Netherlands. The changes that have taken place in European waste legislation since the turn of the millennium are a contributory reason for this trade. For environmental reasons and due to the lack of space, landfill dumping of organic and biological materials has been banned in the whole of the EU since 2005. Incineration with energy recovery is an allowed and in many ways excellent alternative to landfill, although there is a shortage of suitable incineration plants in many countries.

A solution for European countries has therefore become to export their wood waste to Sweden for burning in Swedish district heating stations. Pure wood waste is fired in ordinary boiler stations, and certain assortments of impregnated wood are fired in waste incineration plants connected to district heating networks. However, particularly toxic materials may be burned only in a few special plants in the country, such as at the Sakab Company in Kumla. Swedish energy companies that have participated in this trade have also benefited from it, since they were using fuel purchased at a low price. Recycled wood chips are used as fuels in more than twenty district heating stations around

Sweden. But certain types of wood waste cannot be fired in just any plant. This applies mainly to impregnated wood that makes strict demands on the treatment system of the plant, so that combustion will not lead to emissions of environmental toxins. For this reason, the burning of sleepers, for example, or of other impregnated wood in domestic fireplaces is completely banned.

The fact that German waste wood has been fired in Sweden instead of in its country of origin has been of benefit also in terms of energy and the environment, since the average Swedish plant recovers more than twice as much energy from the waste as an average German plant. However, it is doubtful whether the volume of this trade will be much greater than it is today, since countries that are now exporting recycled wood to Sweden aim to build their own handling capacity in order to gain the benefit of the resource that waste wood actually represents. Many EU countries will find it difficult to reach the national targets set out for the emission of greenhouse gases, and they probably want to utilize every resource that could help them to lower their emissions.

Inexpensive transport by sea

Even though Sweden has large forest resources that we can use for energy applications, we also import large quantities of pellets and chips for generating electricity and heat in our district heating plants. Considering our vast domestic raw material resources, this may appear a little strange at first sight. But this import is not principally due to a shortage of Swedish biomass fuels but is also a matter of price. As an example, Sweden imports large quantities of biomass fuels from the Baltic States, where the costs of production are much lower than in Sweden.

What may perhaps be surprising is that large quantities of pellets are transported across the Atlantic from Canada to Sweden. Can that really be economically viable? Yes – Canadian pellets are transported to the district heating plants by sea. In certain cases, the fuel can be transferred directly from the cargo holds of the

Transport distances for Euro 20 per tonne

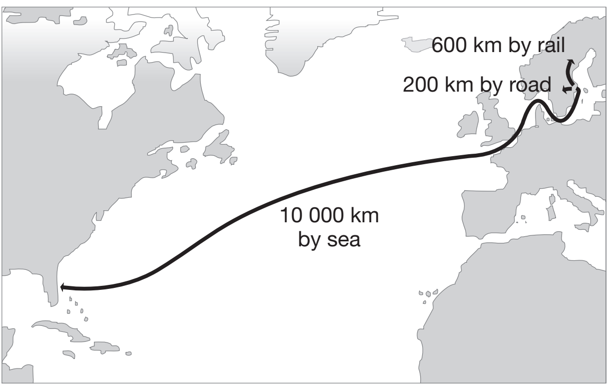


Figure 1. Approximate transport costs by different means of transport. For Euro 20 per tonne, biomass fuel can be transported 200 km by road, 600 km by rail and 10 000 km by sea. (Source: Bo Hektor and Henrik Lundberg at Talloil)

ship to the district heating boiler. A minor part of the domestic biomass fuel transport also takes place by sea from the coast of the Norrland region in northern Sweden to the Stockholm region, although domestic biomass fuel transport usually takes place by road and rail. Figure 1 shows that it is much less expensive to transport large quantities of biofuel by sea than it is by road or rail. As a result, it may be much less expensive to transport biofuel to southern Sweden from Canada than it is from the inland areas of Norrland. The energy consumption for transport is also low in relation to the energy in the pellets transported. The favourable transport economy obviously presupposes that the district heating plant that buys the fuel is either on the coast or on Lake Mälaren which, although a lake, is connected to the Baltic Sea by the Södertälje Canal that is navigable by large ships.

Waste wood – both an environmental risk and a resource

The fact that interest in waste wood as a resource has increased in recent years is due to increased environmental problems as a result of the previously deficient handling of disused wood products and due to increased awareness of the importance of putting all resources to use in society. In the past, the vast majority of waste wood was used for landfill, which resulted in high emissions of the greenhouse gas methane from decomposing wood items. In the case of wood that was pressure impregnated, such as rail sleepers and telephone posts, disposal as landfill also caused emissions of environmental toxins such as creosote, arsenic and various heavy metals. As a result of the development of flue gas treatment, incineration has now become an environmentally good alternative to disposal as landfill, provided that burning is carried out in plants that use the right flue gas treatment techniques.

New EC legislation has thus banned the disposal of waste wood as landfill, but there is no consensus of opinion in Europe about what should be done with the more than 30 million tonnes of European waste wood. The situation is fairly simple in Sweden, since we burn basically all recycled wood in plants that are connected to district heating networks, but competition for recycled wood has arisen in other European countries.

Competition for the raw material

As an example, Spain has a large fibreboard industry that, in the absence of domestic forest raw materials, has become highly dependent on recycled wood that is ground and used for producing various types of board. This industry is now threatened by the increasing demand for biomass fuel, which raises the prices of recycled wood and substantially increases the raw material costs to the industry.

A similar development is also discernible in Sweden, but this concerns competition for sawdust from the many Swedish sawmills. In the past, sawdust was mainly used for the production of chipboard, but is now used to an increasing extent for the production of pellets. In pace with increasing energy prices, the prices of Swedish sawdust have also increased substantially. This is one of the reasons for the difficulties encountered by the Swedish chipboard industry in recent times.

Trade in biomass fuel will increase

Will biomass fuels from agriculture and forest become a major Swedish export product in the future? In view of the high oil prices and the worrying climate issue, the global use of bioenergy will increase, so that it is also probable that trade in biomass fuels will increase. Sweden is so far a net importer of biomass fuels, but this could change in pace with the growing demand from other countries. But bioenergy is not devoid of problems. Competition with the production of both food and traditional forest products may impede the expansion of bioenergy. The same applies to controversies such as the palm oil mentioned earlier.

It is vitally important that all doubts concerning the sustainability of the production chains be brought to the surface. This will be particularly important since the growing trade in biomass fuels will lead to the fuel being produced further and further away from the place where it is consumed. However, provided that the fuel is produced and transported in a sustainable manner, bioenergy is one of the most important tools for coming to grips with the energy and environmental problems of the 21st century.

Bengt Hillring is Associate Professor of Forest Conservation at the Department of Bioenergy at the Swedish University of Agricultural Sciences in Uppsala. He has long been working on bioenergy issues both in research and in lecturing.

Olle Olsson has been PhD Student since the spring of 2007 at the same Department. His research is focused on the development of international trade in solid biofuels.

The alcohol dependence of the transport sector must be broken

The trend today is that we are shifting from oil dependence to alcohol dependence in fuelling the transport sector. Engine alcohol may be one of tomorrow's fuels, although the risk is that we may be binding our investments in technology and systems that are not the best in the long term. The ambition to develop renewable fuels quickly must not stifle other and more efficient measures in the transport sector, writes Magnus Blinge.

Magnus Blinge, Department for Logistics & Transport, Chalmers University of Technology

Why is it so difficult to determine whether we are taking the right path? It's a good question as regards alternative fuels for the transport sector and any environmental benefits they may offer. Due to the high subsidies for fuels and benefits to motorists who buy environmentally friendly vehicles, the interest in alternative fuels and vehicles has exploded in Sweden in recent years. However, increasing numbers of doubting voices are now being raised about the wisdom of this investment.

Most experts in the field consider that the fuels or perhaps, above all, the production methods used today will not be used in the future, since they are generally not sufficiently energy efficient. The investment in European ethanol from grain products is the result of very successful agricultural lobbying. European ethanol is entirely dependent on agricultural subsidies and protectionist customs duties. Tropical ethanol from Brazil, for instance, is much cheaper and more energy efficient to produce than its European counterpart. The sun is simply more generous in tropical countries, and sugar cane has a higher sugar content than wheat and maize, which makes it better suited for ethanol production. If European ethanol is to stand up to the competition, either an entirely new and efficient production method must be found, or else we must continue to support it economically or by means of customs duties on trade.

Second-generation automotive biofuels

Tropical ethanol from sugar cane has the prerequisites for being an energy efficient and sustainable alternative for many decades to come. However, this presupposes that ecologically sustainable grounds are used for cultivation, that the working environment conditions will be acceptable, and that the risk of displacing other land industries to virgin rainforest areas can be prevented. The remaining problem is then the European efforts to achieve self sufficiency in fuel. Oil dependence is then replaced by alcohol dependence! It is still a negligible proportion (around 2 TWh or 2 percent) of automotive fuels in Sweden that originate from renewable raw material (Figure 1), but that proportion is dominated by ethanol (Figure 2).

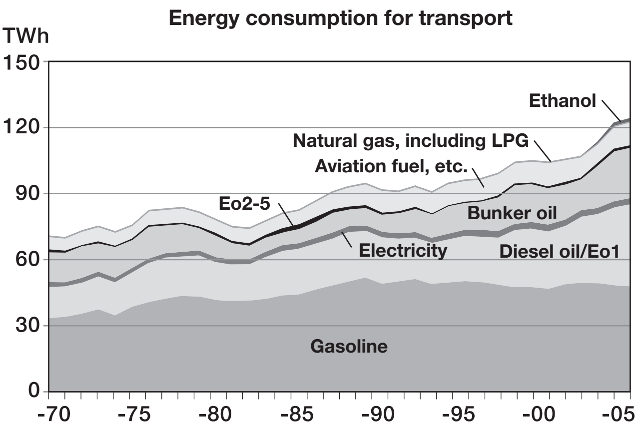


Figure 1. Energy utilization in the Swedish transport sector in 1970–2005 (Source: Swedish Energy Agency)

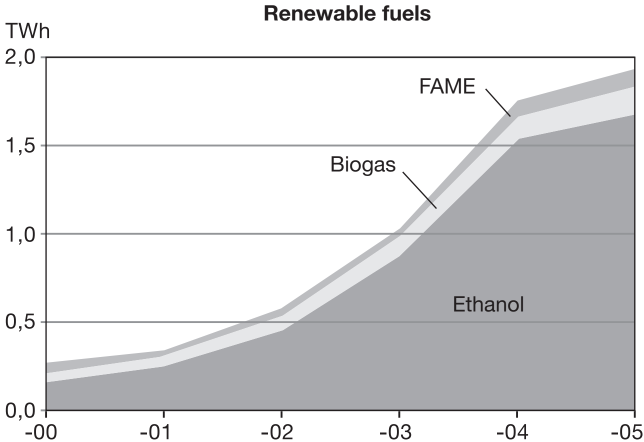


Figure 2. Final utilization of renewable automotive fuels in Sweden in 2000–2005. FAME is the collective name for Fatty Acid Methyl Esters, of which RME (Rape Methyl Ester) is the most common in Sweden today. (Source: Swedish Energy Agency)

A thousand large plants in Europe

Even if we succeed in developing an efficient system for producing automotive fuel in Europe, a number of additional hurdles remain before a large-scale system can be introduced. A holistic view of the problem must be adopted, and we must also begin to plan how our transport and logistics systems, for example, will be designed in a future biomass-based fuel supply system.

Without a doubt, it is theoretically possible to supply the world with renewable energy, since the sun generates many times more energy than we could ever put to use. The problem lies in converting and storing the energy. Biomass can account for a large and important part of the supply, but it must be supplemented with energy efficiency improvements at all stages, and the development of technology for sun, wind and hydropower. Large-scale bioenergy production will naturally affect the environment in many ways. Monoculture cultivation that has consequences on animal and plant life in the areas affected should be avoided to the greatest possible extent. Displacement of wilderness regions, irrigation and competition with food production for a growing world population are other areas that must be taken into account and considered from the sustainability perspective.

However, it is more doubtful whether, from the European perspective, we could be entirely self sufficient in bioenergy for both the energy and the transport sectors. The available land area for biomass production is not where most people live, and we therefore face a serious logistics problem. The quantities of biomass that must be moved are vast. The following example illustrates the extent of the logistics challenge we are facing.

An automotive biofuel production plant that is sufficiently large to be economically viable will need five times as much raw material as that used by a large paper mill in the Nordic countries. This is not impossible to arrange, although it is undoubtedly a challenge from the transport aspect. Considering Poland as an example, three plants of this size would be needed to replace one fifth of today's Polish automotive fuel consumption. If the plants are to be close to the raw material, i.e. close to forest or agricultural land, transport would have to take place by road. Each of these plants would need to be supplied by 450 trucks per day, or one truck every 3 minuets, around the clock, all the year round.

If we expand our scenario and plan to replace 15 percent of the automotive fuel consumption in the EU 15 region (the 15 countries that were members of the EU when Sweden joined), an area corresponding to the whole of Poland would have to be planted with energy forest. 122 plants would be needed, and the siting of these would be problematic. So it is not merely a matter of finding suitable and adequate land area for biomass production. It also involves the need for beginning to plan where these plants would be located and how the logistics could be arranged. The plants would probably have to be close to water, so that transport by sea could be used. If 100 percent of the automotive fuel for EU 15 were replaced by domestic and imported biomass, almost one thousand plants would have to be built. Where could so many places be found along the coasts of Europe? Land area is naturally available, but coastal regions are popular for tourism and recreation, trade, dwellings and industry. Bearing in mind the extensive transport that each plant would need, a very large land area would be affected by the operations.

The above scenarios illustrate that it would be unreasonable to hope that renewable fuels alone would solve the environmental problems for the transport sector. High investments in improved energy efficiency would be necessary, and also a change in behaviour of private motorists and modified regulatory instruments for the goods transport sector in a direction towards less energy-consuming logistics.

Practical barriers to be surmounted

It is naturally not impossible to change over to biologically based automotive fuels. In actual fact, we have no choice in the long term. However, we cannot expect the technology for producing biologically based synthetic fuels to be ready for use before we begin planning for how this could be achieved. If we produce an operational pilot plant within 5–10 years, we may perhaps have the first large-scale plant on stream within 15–20 years. If we are then to begin the process of building one thousand plants on popular, often privately owned land close to the coast, it will take a long time before they can be operational. This is particularly so in view of the infrastructure around the plants that would probably have to be of almost motorway standard to cope with the enormous transport work involved.

Many appeals and environmental analyses would probably delay the process. To ensure that this will not take longer than the time we have available, we should already start discussing this matter too. We must begin to plan the arrangement of the transport solutions for a biologically based fuel system. Would it be possible to implement on such a large scale?

If a biologically based synthetic fuel is to be able to compete with fossil fuels, powerful economic regulatory instruments or complete bans on the use of fossil energy sources must be introduced. Moreover, this must take place on a global level. South Africa now actually produces synthetic fuels from coal. These are economically viable as long as the price of oil is higher than around 50 dollars per barrel. Since sufficient quantities of coal are available in the world for several centuries of consumption, this is the guideline price with which the biologically based fuels must compete. So the fact that the oil resources are beginning to dwindle (or, to be more exact, will be too expensive to extract) does not mean that the availability of relatively inexpensive, fossil liquid fuels is coming to an end.

Part of the solution to the problem is to build the plants closer to the raw material, i.e. the tropics, where biomass grows quickest. The condition is naturally that the production in these countries takes place in an ecologically sustainable and ethically correct manner. We would then have to distribute only the finished fuel in volumes that we are already distributing now. Europe would then avoid the logistics problems, but we would end up in a situation in which we continue to be dependent on energy from other regions of the world. Oil dependence is undoubtedly one of the most important driving forces for the development of alternative fuels in the western world.

The holistic perspective must also consider the question of whether it is the transport sector for which the available biomass should be used. It is beyond any doubt that both economically and from the energy aspect it is better to replace fossil-fired electricity and heat generation with the available biomass than to make automotive fuel out of it. So why produce automotive fuel in the first place? One of the factors is dependability of supply. The transport industry is very important to modern society, and much of industrial production is based on flexible and relatively inexpensive transport. So should the transport industry be the only sector that is 99 percent dependent on fossil energy? Is it acceptable in the long term with regard to the environment and dependability of supply? The problems of greenhouse effect and oil dependence are growing year by year, and the risk of wide future variations in supply and price due to these problems cannot be excluded. What would a rationing situation mean to industry? So there are reasons, in addition to purely environmental considerations, for breaking the total dependence of the transport system on liquid fossil fuels.

Renewable fuels versus other possibilities

Against the background of the above reasoning, the most important issue as regards coming to grips with the climate problem is clearly for the transport sector to improve the efficiency of the entire energy consumption in the system. It involves ensuring that vehicles and the entire transport system use as little energy as possible, and that the available energy is used and converted where it is of greatest benefit.

The transport sector must naturally also become fossil-free in the future and be powered by renewable fuels. But the practical problems of producing sufficient quantities are so vast and so numerous that we must also concentrate on reducing the needs if we are ever to be able to cope with it. It would be most dangerous if we allowed ourselves to be deceived into believing that it is only a matter of time before alternatives are here and that we should therefore invest even more time, money and effort into developing these fuels as quickly as possible. This would prevent other more essential and cost-effective measures. Small and more fuel-efficient passenger cars, more efficient and less energy-intensive logistics and transport systems, and regulatory instruments that guide us in the right direction are essential conditions that would enable us to see alternative fuels as a possible solution. If we improved the transport system efficiency by a factor of 10 by technical measures and by changed attitudes and changed behaviour, which I believe would be possible, so that the system would become 10 times less energy-intensive that it is today, we would have an opportunity of becoming self-sufficient in Europe. We would not need a land area corresponding to seven times the area of Poland, but perhaps corresponding to one or two, and we would not need as numerous and as large production plants. We could solve the problems with such a system approach, but we would not solve them by believing that alternative fuels alone will solve our problems.

To be able to implement the necessary changes in attitude and behaviour, great political courage and a long-term approach would be necessary. Economic regulatory instruments, clear long-term targets and consistent action would make it possible to reach the targets set by the Swedish Commission against Oil Dependence for reducing the consumption of diesel oil and gasoline by 40–50 percent. But research and development must not be allowed to one-sidedly veer in one direction and focus on measures that are populistically appropriate at any particular time, and where organizations that have the strongest lobbying organizations are allowed to steer the agenda.

We must dare to venture

Should we venture to find alternative fuels for the transport sector? We obviously must! However, as mentioned earlier, this must be done with a systemic view, and we must not allow the ambition to develop fuels and vehicles quickly in large quantities to suppress other, more effective measures. Why is the Swedish vehicle population 25 percent thirstier on fuel than that of our neighbouring countries? How are tax subsidies environmentally justified by tax allowances for long-distance commuting to work by car?

Trucks now look like rolling square boxes. This is not the form that comes to mind when aiming to minimize the aerodynamic drag and thus the fuel consumption. By changes to the permissible vehicle lengths that would allow for spoilers, etc., the aerodynamics of trucks could be improved so that the fuel consumption would be reduced by around 25 percent. The climatic result of the reduction would produce roughly the same effect as mixing 40–50 percent of RME or ethanol into the fuel system – but would be much more efficient, quicker, less expensive and environmentally more sustainable.

We are in a situation in which we have many different possibilities, and in which all alternatives have their advantages and disadvantage. We cannot know with any degree of certainty what technical solutions will emerge in 20–30 years. Will it be liquid or gaseous fuels? Will it be Otto engines or diesel engines? Will it possibly be electric motors, hybrids or other combinations, or conceivably fuel cells? What we do know with certainty is that the future will not be as we believe it will be. We should therefore be careful and not progress too far and invest ourselves firmly into technology and systems that are promising today, but that are likely to entrench the wrong technology for the future.

But we must not let the vision of the best obscure the path towards what is better. It is all a matter of balance. We must dare to make mistakes and be prepared for making mistakes, but we must still dare to try. Future generations will forgive us if we have made mistakes at times, but they will never forgive us if we fail to even try.

Magnus Blinge is Doctor of Technology and, when he wrote the article, he was university lecturer at the Department for Logistics & Transport at the Chalmers University of Technology. He has researched into the development of methods for life cycle studies of vehicle fuels, environmentally appropriate logistics and cost-effective environmental solutions for the goods transport sector. He is now the head of the unit for Transport at VINNOVA.

We should use bioenergy efficiently

Do we need to make efforts to use bioenergy efficiently? Yes, because bioenergy is a limited energy resource. The more efficiently we can use biomass fuels, the more we will be able to reduce our oil dependence and carbon dioxide emissions. With today's technology, it is climatically more efficient to generate heat and electricity than automotive fuels from biomass, writes Leif Gustavsson. But new technology is coming and will improve the climate efficiency of automotive fuels.

Leif Gustavsson, Institution for Technology, Physics and Mathematics, Mid-Sweden University.

Photo: Jens Blixth

Bioenergy is an important part of Sweden's energy system. The use of bioenergy has roughly doubled in the past 20 years, and the biomass fuel price has simultaneously halved in real terms, i.e. in relation to the development of prices in general. Before this expansion, bioenergy was used principally in the forest industry and for small-scale heating. The availability and possible extraction of biomass fuels were discussed in Sweden in the 1980s. The forest companies expressed their concern over the fact that the extraction of biomass fuels would impair the raw material supply to the forestry industry and that the price of biomass fuel would rise. The high expansion rate of bioenergy consumption and the price reductions in real term in recent decades demonstrate that Sweden has developed an efficient bioenergy sector. New companies, often linked to the forestry industry, have emerged for commercializing bioenergy.

Reduction in the dependence on imported oil and reduction in the net emissions of carbon dioxide were the two most important driving forces towards increased consumption of bioenergy in recent decades. The strengths of the two driving forces have varied over time. The rise in crude oil prices in recent years and the increasingly intensive discussion on climate change have demonstrated the need for reducing both oil dependence and carbon dioxide emissions.

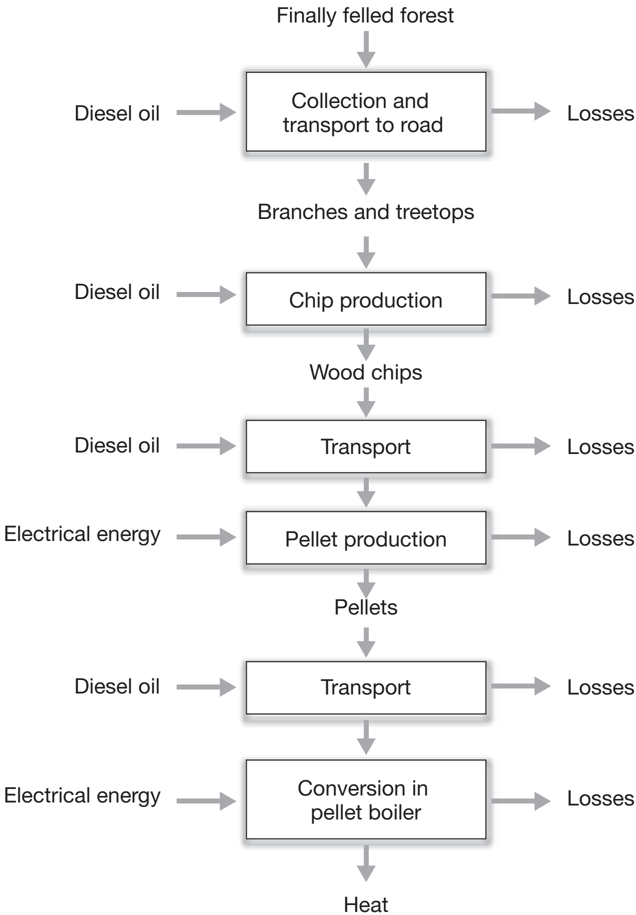


Figure 1. The figure shows a bioenergy system for heat generation, using pellets from branches and treetops from final felling of the forest. The input energy in the form of diesel oil and electricity is shown to the left in the figure. Wood losses, both physical and from biological decomposition or thermal losses during the conversion are shown to the right.

Land area is the limiting factor

Bioenergy is a limited resource. The more efficiently we can use it, the more we will be able to reduce our oil dependence and the carbon dioxide emissions from a given quantity of biomass fuels. Bioenergy systems can be designed in many different ways for producing automotive fuels, electricity and heat. We can use bioenergy in small plants for heating single-family houses or in large plants for heating a whole city. How should we design the bioenergy systems and which fossil systems should be replaced in order to reduce effectively both our oil dependence and our carbon dioxide emissions?

The point of departure for such an analysis may be to achieve maximum reduction in both oil dependence and carbon dioxide emissions at the lowest possible cost. This means that the bioenergy systems must be energy efficient all the way from the natural resource to the energy service delivered. In the bioenergy systems themselves, wood losses will occur – both physical losses (such as spillage and biological decomposition) and thermal losses in the conversion process. Input energy is also needed for running the system (Figure 1).

A low input energy, i.e. the energy used for building, running and dismantling the bioenergy system, increases the amount of net energy supplied to the end consumer for a given amount of gross energy. An example of the input energy is the consumption of fuel for extracting and transporting the biomass fuel. What we want to maximize is the amount of net energy in the form of energy services delivered to the end consumer, such as refrigeration, mechanical work, transport work and heat in buildings, for a given quantity of natural resource. Net energy is the amount of energy that reaches the end consumer after deduction of losses in the bioenergy system itself and the input energy for building, operating and dismantling the system. The input energy to the bioenergy system is supplied by a different energy system, often a fossil-fuelled system. The losses in these energy systems and the input energy to them should be taken into account and added to the input energy for the bioenergy system.

Losses occur and input energy is needed when processing biomass into briquettes, pellets and liquid fuel. The advantages and disadvantages occurring in processing must be weighed against one another. The benefit of processing at a later stage must be greater than the losses and input energy in the processing.

In total, this means, for example, that in the extraction of forest fuel in the form of branches and treetops during final felling of forests, we select a system that, after final conversion, gives maximum net energy to the end consumer per unit of felled land area. Energy plantations on agricultural land need also be arranged to maximize the amount of net energy to the end consumer per hectare. It is the felled land area and cultivated land area that ultimately restrict the extraction of bioenergy. The input energy reduction should be carried out with care. As an example, fertilizing in order to increase the growth of energy crops increases the input energy, although this is justified as long as the net energy that reaches the end consumer increases.

Energy balances for different forest fuel systems

The processing of biomass incurs costs. But processing can also facilitate the practical handling of biomass and can therefore be justified. Bundling together or chipping branches and treetops (slash) may be more efficient than the handling of loose slash. The processing of biomass is often beneficial to transport and end consumption, although the wood losses and input energy may be significant.

Figure 2 shows the net amount of energy that reaches the end consumer from one hectare of forest land for different forest fuel systems if end consumption takes places locally, nationally or internationally. Fuel systems with slash logs (slash that is compacted and bundled together into a log) and chips are shown in the figure. Slash logs are expected to be delivered to major users who have the equipment necessary for effectively chipping the logs. In local consumption, it is assumed that the biomass fuels are transported around 80 kilometres by road, while in national and international use, around

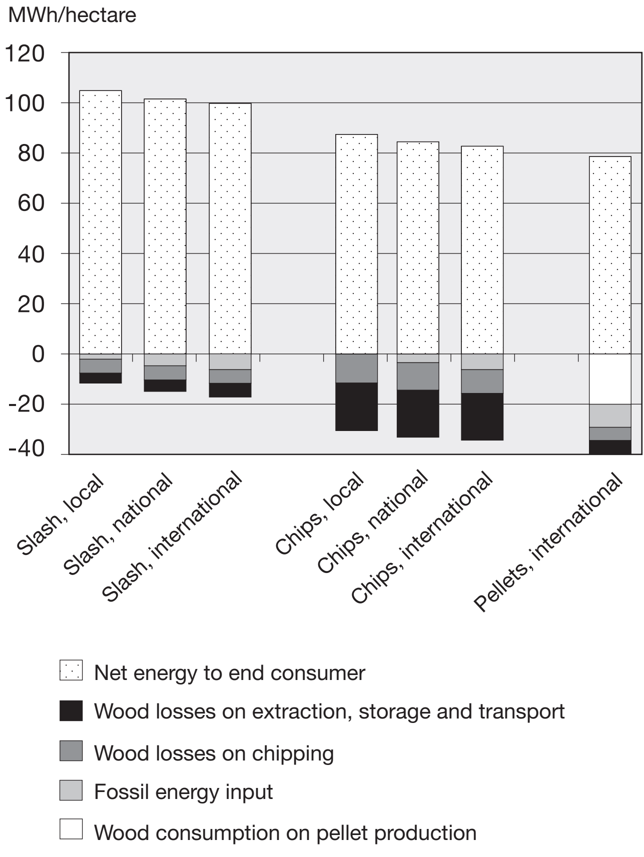


Figure 2. Energy balances on extraction of slash by means of different forest fuel systems per hectare of finally felled forest land. The forest fuel is used locally, nationally or internationally. The energy that reaches the end consumer is shown as positive values. The wood losses in the bioenergy system itself and the input energy are shown in the figure as negative values. In the pellets alternative, extraction from the forest takes place with slash logs.

700 and 1400 kilometres by road, rail or sea. The wood losses in the bioenergy chain itself and the input energy are shown as negative values in the figure. Processing into pellets facilitates the transport and is therefore of greatest value in long-distance transport. The energy balance for pellets in the figure is therefore shown for long-distance transport, i.e. for international use. Figure 2 shows that the transport distances have little influence on the amount of energy reaching the end consumer,

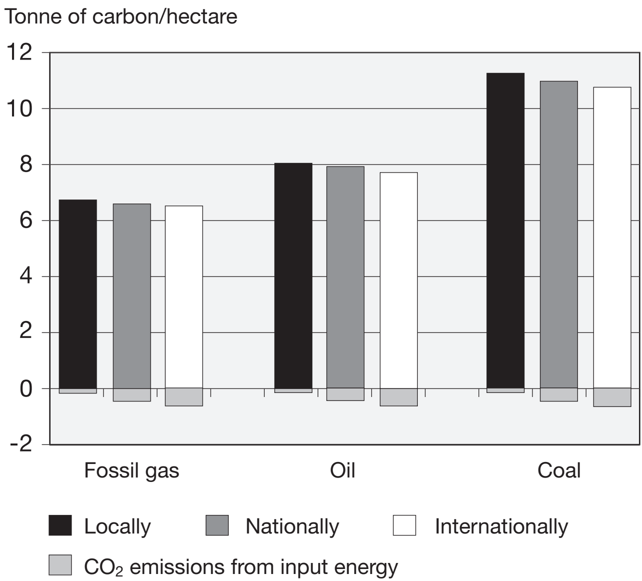


Figure 3. Net reduction in carbon dioxide emissions when different fossil fuels are replaced by biomass fuel (branches and treetops) locally, nationally or internationally per hectare of finally felled forest land. The carbon dioxide emissions from the input energy to the biosystem are shown as negative values. The transport distances and means of transport are the same as in Figure 2.

but the choice of forest fuel systems and the processing into pellets is of relatively major importance. Using slash logs with large-scale, efficient chipping gives most net energy to the end consumer even in long-distance transport.

Carbon dioxide emissions decrease by different amounts

The carbon dioxide emissions vary for different fossil fuels. The emissions are highest in the combustion of coal and lowest in the combustion of fossil gas (natural gas). Figure 3 shows the net reduction in carbon dioxide emissions when different fossil fuels are replaced by biomass fuel at local, national or international consumers. The carbon dioxide emissions from the input energy are shown as negative values. The figure shows that which fossil fuel that is replaced is of much greater importance than whether the fossil fuel is replaced locally, nationally or internationally. The transport distances are of subordinate importance.

Figure 3 shows that we should give first preference to replacing coal, then fossil oil and finally fossil gas for achieving maximum reduction in carbon dioxide emissions. To reduce oil dependence we must obviously reduce the consumption of oil.

More efficient generation of electricity and heat

If we want to use wood-type biofuels in the transport sector to replace diesel oil and gasoline, we must process them to liquid fuel. No such processing is needed for generating electricity and heat, and the energy efficiency will therefore be higher in such bioenergy systems. This also applies to the comparison with new and more efficient technique for ethanol production. If we generate electricity and heat in the same plant (combined heat and power, CHP) we will also achieve a high efficiency in such an energy system compared to generating electricity and heat separately.

The expansion of district heating in Sweden offers good opportunities for combined generation of electricity and heat. More numerous buildings, principally those heated with electricity and oil, can also be connected to the district heating system. This applies particularly to single-family houses, less than 10 percent of which are connected to a district heating system.

Replacing electric heating with district heating is of particular interest. This reduces the consumption of electricity and increases the opportunities for CHP generation. A district heating system is utilized much more efficiently for generating electricity if we employ a new technique whereby wood-type biofuels are gasified and used in a gas turbine and a steam turbine for generating electricity. We can almost double the electricity generated by this technique compared with the technique used today. We can thereby increase the efficiency in the utilization of bioenergy. But even if we expanded the district heating systems to the maximum possible extent, we would still not be able to use CHP generation to produce all of the electricity we consume. The heat lost with the cooling water from today's Swedish power generation (principally from nuclear power plants) is roughly three times as high as the heat delivered from today's district heating plants. We have a large surplus of waste heat.

District heating is not a competitive alternative in sparsely populated areas. In these areas, electrically driven heat pumps can be used for heating by using groundwater, surface water or surface soil as the source of heat. Even if electricity is generated in separate power generation plants fired with biomass fuel, it is more energy-efficient and cost-effective to use heat pump technology than wood pellet fire boilers, provided that a suitable source of heat is available for the heat pump system. Pellet-fired boilers are otherwise a good heating alternative.

The electricity system in Sweden is becoming increasingly integrated with the electrical systems of other countries. In the EU, electricity is often generated in large coal-fired plants. As the power demand increases or decreases, it is often economically beneficial to adjust the power output of these plants accordingly. The integration of the electrical systems of the EU could then be expected to allow biofuel-fired power generation in Sweden to replace the electricity generated by coal-fired plants in the EU. This would be a very efficient way of using bioenergy to reduce carbon dioxide emissions. The increased use of bioenergy in Sweden would then result in reduced carbon dioxide emissions outside the country's borders.

The ethanol chain requires a great deal of energy – in spite of the new technique

Can liquid fuels be produced from wood-based biomass at high efficiency? Yes – a new technique such as black liquor gasification is being developed for use in the chemical pulp industry. This technique enables liquid fuels (methanol, dimethyl ether) to be produced with high efficiency. Co-production of liquid fuels in the pulp industry for use in the transport sector would reduce the carbon dioxide emissions and oil dependence, while minimizing the conversion losses. The potential annual fuel production using this technique would be equivalent to just over half of today's diesel oil consumption in the Swedish transport sector or 15–20 TWh.

But the dominance of ethanol as vehicle fuel in Sweden is still the subject of discussion. Most of the ethanol used is produced by fermentation of grain or is imported from countries in which it is produced from sugar cane or maize. A new technique is being developed to enable ethanol to be produced from wood-based fuels. The technique is expected to be much more efficient in the life cycle perspective than today's technique for the production of ethanol from grain. But the losses in the conversion of wood-based biomass to ethanol are still high.

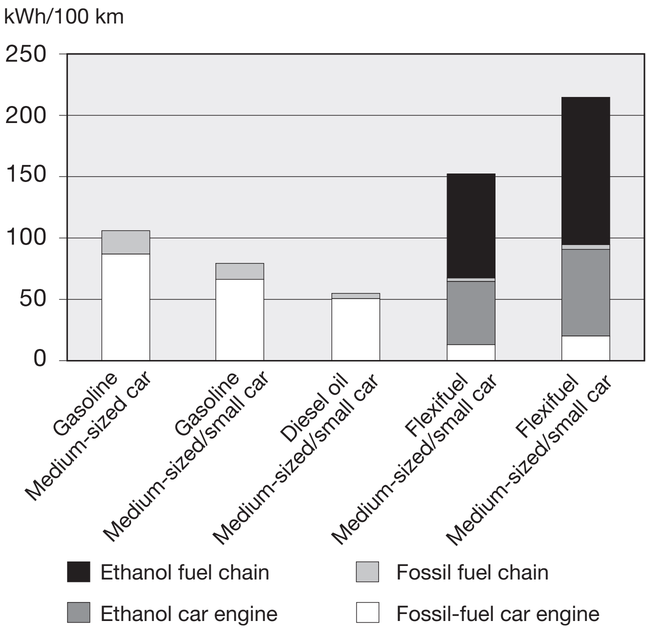


Figure 4. Energy consumption over the fuel chain for some of the most widely sold car brands (Saab 9-5 and Volvo V50 and V70) in Sweden in 2006 for some different types of fuel. Both the fuel consumption of the car engine and the energy use in the fuel chain for producing and distributing the fuel are shown in the figure.

Figure 4 shows the fuel consumption of the automotive engine and the energy needed in the fuel chain for producing and distributing the fuel for some of the most widely-sold cars in Sweden in 2006 (Saab 9-5 and Volvo V50 and V70). It is assumed that the ethanol is produced from wood-based biofuels using a technique that is in the course of development and that has good technical performance. The energy consumption of a small to medium-sized car (Volvo V50) with a small diesel engine and manual gearbox is just over 50 kWh per 100 km on a mixed cycle if the energy consumption is considered over the entire fuel chain. The same car with a Flexifuel engine running on 85 percent ethanol and 15 percent gasoline will cause the energy consumption over the fuel chain to be almost three times higher. This represents inefficient utilization of bioenergy.

The difference is much smaller if only the consumption of fuel in the car engines is compared. This demonstrates the importance of taking into account the energy use over the whole of the fuel chain from the natural resource up to and including the end use in the engine itself, if adequate comparison is to be made between different types of fuel. The figure also shows that the size of the car is very important to the fuel consumption and thus to the energy use over the fuel chain.

Combined heat and power generation is environmentally more efficient

Figure 5 shows the fossil carbon dioxide emissions for the same car brands and fuels as in Figure 4. The figure also shows the carbon dioxide emissions that are avoided (A) if the amount of biomass fuels used for producing ethanol is used instead for replacing oil in oil-fired boilers. If ethanol is used in a small to medium-sized car, the carbon dioxide emissions will be about 2.5 times higher than those from the same car with a diesel engine. This applies if it is taken into account that a major carbon dioxide reduction is "missed" by using biomass for ethanol production instead of generating heat or electricity. This demonstrates how important it is to take into account different alternative ways of using the limited bioenergy resource.

It is important to reduce oil dependence in the transport sector and also to research and develop alternatives. Swedish cars have much higher fuel consumption than the average in the EU. It is therefore possible to reduce the fuel consumption significantly by having smaller cars and more energy-efficient engines and drive systems. Ethanol requires small modifications to the engine and fuel distribution system and is easy to adapt to today's fossil fuel systems. But does Swedish ethanol contribute to a sustainable development of society?

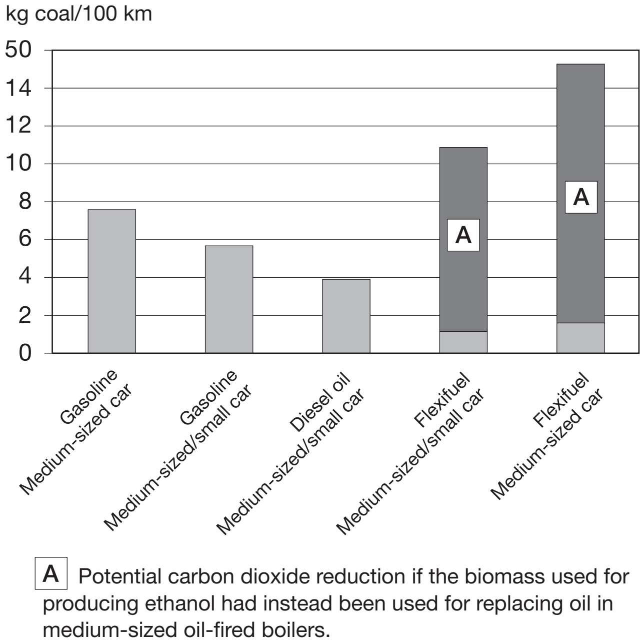


Figure 5. Carbon dioxide emissions over the entire fuel chain from some of the most widely-sold car brands (Saab 9-5 and Volvo V50, V70) in Sweden in 2006 for some different types of fuel. The figure also shows the potential carbon dioxide reduction achieved if the biomass used for producing ethanol had instead been used for replacing oil in medium-sized oil-fired boilers.

Strategy for reducing both oil consumption and carbon dioxide emissions

The consumption of diesel oil and gasoline corresponds to almost 60 percent of the final consumption of oil products in Sweden. Industry, power generation and heat generation for district heating account for almost 20 percent of the consumption of oil products, while dwellings and services account for just over 15 percent. We have shown that if we prioritize reduction in carbon dioxide emissions, it is most efficient to use bioenergy for generating electricity and heat. To reduce oil dependence in the transport sector, efficient methods should be used for fuel production. This favours black liquor gasification for fuel production and not for electricity generation, which is also possible. If most of the oil consumption in industry, electricity generation and heat generation and in dwellings and services is replaced, the final consumption of oil products could be reduced by perhaps 40–45 percent.

The pattern of carbon dioxide emissions differs from the pattern of oil product consumption. Transport accounts for more than 35 percent of the carbon dioxide emissions, while industry, including power stations, gasworks and district heating boiler stations account for just over 50 percent (Table 1). Carbon dioxide emissions are reduced significantly if coal is replaced by biomass fuels. Coal is used in industry and, to a certain extent, also for power and heat generation.

Table 1. Swedish carbon dioxide emissions in 2004 in various sectors in millions of tonnes of carbon dioxide and in percent.

Sector	Carbon dioxide emissions (million tonnes)	Carbon dioxide emissions (percent)
Combustion in industry	11,4	20,6
Industrial processes	4,7	8,5
Transport	19,9	35,9
Dwellings and services, etc.	6,0	10,9
Combustion in power stations, gasworks and district heating stations	12,4	22,5
Diffuse emissions	0,9	1,6
Total	**53,4**	**100**

If we prioritize both reduced oil consumption and reduced carbon dioxide emissions, a good strategy would be to proceed as follows:

- replace oil products and coal used for electricity and heat generation and in industry by biofuel-fired plants, principally for combined heat and power generation (CHP) with a high electricity yield
- replace electric heating and oil-fired heating in dwellings and services, primarily with biofuel-based district heating designed for combined heat and power (CHP) generation with a high electricity yield
- replace fossil automotive fuels with bio-based automotive fuels produced with high efficiency

Biomass fuels can also be used in industrial processes such as in the production of iron and steel. In this area, there appear to be interesting possibilities of using biomass fuels instead of coal and to reduce the emissions of carbon dioxide by ensuring high efficiency. Another interesting area is materials substitution, e.g. replacing concrete with wood-based materials. Carbon dioxide emissions could then be reduced, since the input energy is often lower for producing wood material than other materials, since the wood-based by-products and residual products can be used for replacing fossil fuels, and also since carbon dioxide emissions can be avoided in the production process itself.

Leif Gustavsson is Professor of Ecotechnology at the Mid-Sweden University. He researches into energy and materials systems, and especially how biologically based systems can be designed and implemented for effective reduction of greenhouse gas emissions and for reducing the use of fossil fuels.

Bioenergy systems – which are the most efficient?

How should biomass fuels be used as efficiently as possible? Should we use them for generating electricity and heat, or should we convert them into vehicle fuel? It would be difficult to make a general assertion. But what is certain is that forest fuels, energy forest and unused residual products are efficient in terms of energy, the environment and costs, writes Pål Börjesson. Moreover, biorefinery concepts in which many different commodities are produced, including heat, electricity and vehicle fuel, appear to be efficient.

På Börjesson, Environmental and Energy Systems, Lund Technical University

The issue of how biomass fuels should be used in order to employ them as efficiently as possible is currently the subject of discussion. Some claim that biomass fuels should be used for generating electricity and heat, since this leads to a greater reduction in the emission of greenhouse gases than if they were converted and used as vehicle fuel. The underlying argument is the greatest possible carbon dioxide reduction at the lowest cost.

Others claim that bioenergy should also be used for producing vehicle fuels, since most of our oil consumption is in the transport sector. The supporting argument

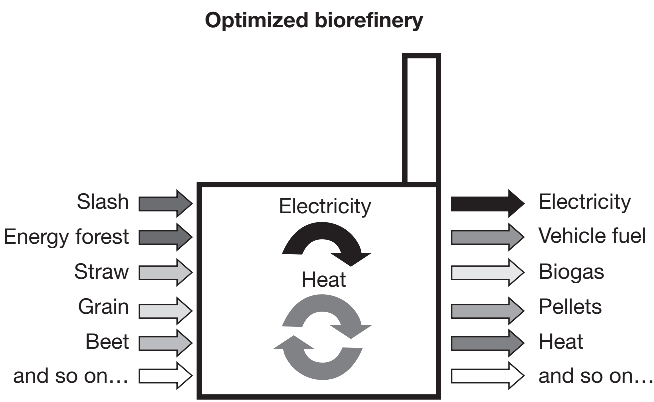


Figure 1. Future biorefinery concept in which various biological raw materials are utilized in an optimized manner by joint production of various energy carriers. This leads to synergy effects in the form of improved resource efficiency compared with the conditions where each energy carrier is produced individually.

here is that bioenergy is needed for breaking our oil dependence. But we may perhaps be able to find a third way in which we use new, efficient systems for producing electricity, heat and vehicle fuel at the same time in plants known as biorefineries (Figure 1). We would then be able to achieve energy-efficient vehicle fuel production, since energy combines have high overall efficiency with low conversion losses. In the future, today's debate on either automotive biofuel or electricity and heat from biomass fuels may thus appear to be fairly superfluous.

Four aspects of sustainable bioenergy systems

Bioenergy systems can be defined as efficient in different ways. One way of defining bioenergy systems with long-term sustainability is to include the following four aspects:

- *Resource efficiency.* This means, for example, that agricultural land for energy production should be used for producing as much biomass fuel as possible, i.e. high-yield energy crops should be used instead of low-yield crops. Unused residual products in agriculture and forestry, such as straw and manure, as well as branches and treetops (slash), should be used as far as possible for energy purposes.
- *Energy efficiency.* Energy losses must be minimized throughout the bioenergy chain, from production to final use. The energy input in the production of energy crops should be as low as possible in relation to the bioenergy harvest obtained. In addition, the

energy losses in the conversion of biomass to electricity, heat and vehicle fuel should be as low as possible. Finally, the refined bioenergy should be used with high efficiency.

- *Environmental efficiency.* The use of new bioenergy systems should lead to the highest possible reduction in greenhouse gas emissions. At the same time, it must not lead to local environmental problems. The cultivation of energy crops or the extraction of forest fuels should preferably lead to an improvement in the local environment. The conversion and use of bioenergy must not cause increased emissions of atmospheric pollutants.
- *Cost efficiency.* First preference should be given to the least expensive biomass fuels, which are often various types of residual products. Energy crops produced at low cultivation costs should be selected in preference to those that involve high cultivation costs. Cost-efficient technique should be used for the conversion and refinement of biomass fuel, and the end use of bioenergy must not involve expensive special techniques.

Resource-efficient bioenergy systems

Since arable land is a limited resource and must be used at the same time for food, animal feed and raw materials production, energy cultivation with the highest possible yield should be used. This will enable forest and agricultural land to go much further for producing bioenergy that can replace fossil fuels. Scope is also available for extracting much more residual products, such as slash from forestry and straw from agriculture, for energy purposes. Manure and tops and leaves from sugar beets, for instance, can be used for biogas production, which is used to a very small extent today.

The energy harvest that various energy crops can produce per hectare of arable land may differ fairly widely (Figure 2 relates to cultivation on good arable land in the southernmost part of Sweden, i.e. southern

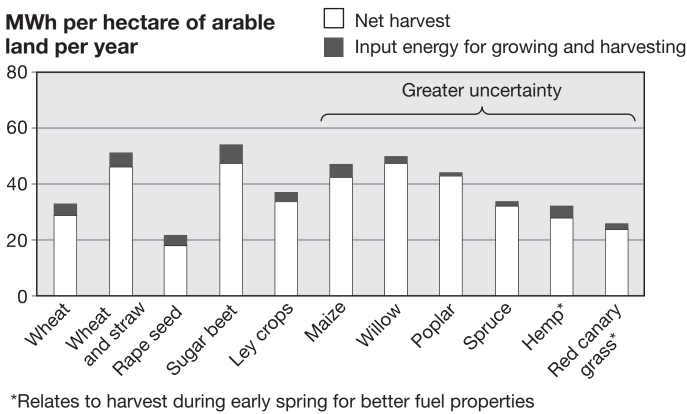


Figure 2. Energy harvest for various crops expressed as net harvest (white part of the bar) and gross harvest (the entire bar) grown on good arable land in southern Götaland in southernmost Sweden. The grey part of the bar represents the input energy necessary for growing and harvesting the corresponding crop, i.e. the difference between net and gross harvest.

Götaland). Moreover, harvests differ between various parts of the country. On the best arable land in southern Götaland, the energy harvest may be up to six times higher per hectare than in the Norrland region in northern Sweden, the actual figure depending on the energy crops grown. Moreover, there are wide local variations in harvest per hectare, even within one farm. If somewhat poorer arable land is used for energy cultivation, the bioenergy contribution of agriculture will drop compared to the yield from average or somewhat better arable land.

Energy input for various systems

A way of describing how energy efficient biomass fuels are to produce is to calculate their energy balance. Energy balance means a comparison between the energy harvest and the input in the form of auxiliary energy necessary for cultivation and harvesting. Energy balance can be expressed, for instance, as the magnitude of the auxiliary energy in relation to the gross harvest, expressed in percent. The lower the energy input required per unit of energy of the biomass produced, the higher the energy efficiency of the production system. The input energy includes both direct energy consumption, such as diesel oil for tractors and forest machines, and indirect energy consumption in the form of, for instance, mineral fertilizer, pesticides, and manufacture and maintenance of machines. All auxiliary energy has been recalculated to so-called primary energy, i.e. also including the energy used for producing diesel oil or electricity, for instance. Figure 3 shows the energy balance for the production of various biomass fuels in southern Götaland, including the transport distance of 50 km by road to the energy plant.

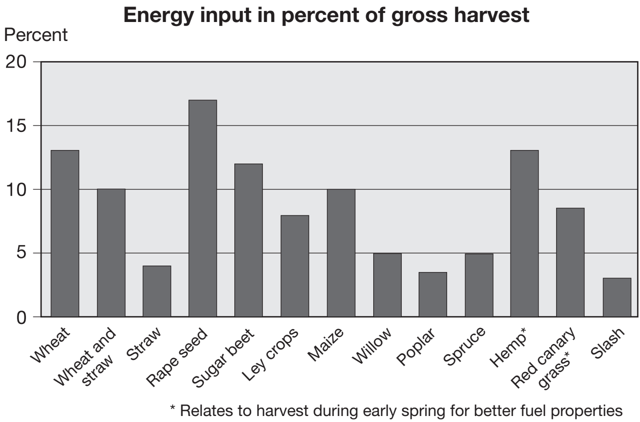


Figure 3. Energy balance for various biomass fuels cultivated in southern Götaland, expressed as the magnitude of the energy input in percent of the gross harvest. The energy input includes auxiliary energy for production and transport 50 km to the energy plant.

The removal of slash from the forest and straw from agricultural land requires little input energy, i.e. between 3 and 4 percent of the energy content in the gross harvest. The magnitude of the energy input may vary somewhat with local conditions and depends on the transport distance, although this is of minor importance from the energy aspect than would appear at first sight. If forest chips are transported by road for

150 km instead of 50 km (as shown in Figure 3), the input energy would increase from about 3 to 5 percent.

Other energy efficient bioenergy systems are the cultivation of energy forest (willow, poplar, hybrid aspen and fertilized spruce), which is almost always on a level with the removal of residual products such as slash and straw. This is followed by the cultivation of other perennial energy crops such as grassland and reed canary grass, for which the energy input is normally less than 10 percent of the energy harvest. The energy input for annual energy crops that require ploughing, sowing and harvesting every year varies between 10 and 17 percent of the energy harvest.

If growing, harvesting and transport of energy crops is done by means of only biofuel-based energy input instead of principally fossil fuels as they are today, the input energy would increase by 30–45 percent. The increased input of primary energy is due principally to the fact that the conversion of biomass to fuel leads to higher energy losses than when crude oil is refined to diesel oil and gasoline. In this case, the input of auxiliary energy in energy forest cultivation, for instance, would increase from around 5–7 percent of the energy content in the gross harvest.

Energy losses on conversion

Energy losses will occur when biomass fuels are converted to heat, electricity and vehicle fuel. The losses are normally small (10–20 percent) when slash, energy forest, straw, etc. are fired for heat generation. Electricity generation can also take place efficiently by heat and electricity being generated simultaneously in combined heat and power (CHP) generation. In CHP generation plants, around one third of electricity and two thirds of heat can be generated per unit of fuel, with the same high overall efficiency as when only heat is generated.

The energy losses in the production of biomass-based vehicle fuels are often higher, and the yield of fuel can vary between 35 and 70 percent of the energy content in the biomass, depending on the conversion technique used and the fuel produced. Expressed per hectare of arable land, twice as much energy can be obtained in the form of heat (and electricity by CHP generation) than vehicle fuel from energy cultivation using today's vehicle fuel production system.

Animal feed is a by-product worth considering

The energy balance for ethanol from grain is sometimes discussed, and it is claimed at times that this is negative, i.e. that more energy is needed for producing the ethanol than the energy contained in the fuel. But almost all Swedish and international energy balance studies arrive at a positive energy balance, and that the magnitude of the energy input often varies between 40 and 75 percent of the gross ethanol yield. The results may vary even more widely, depending on how the calculations are made. This variation is highly dependent on how the energy input is distributed between fuel and the by-products produced. When ethanol is produced from grain, the distiller's waste obtained is used as animal feed, and if this is not taken into account, the energy balance will be poorer. On the other hand, if this distiller's waste is assumed to replace the soy protein feed imported from South or North America, the energy balance may be appreciably better, since a great deal of energy is needed for producing and transporting the imported protein feed.

If fuel is produced from rape seed (rape methyl ester, RME), the by-product obtained can be used as animal feed that can replace imported protein feed. If ethanol and RME factories are regarded as combined vehicle fuel and animal feed factories, they will be much better from the energy aspect than if they are regarded only as vehicle fuel factories. The market and demand for animal feed determine the extent of the energy benefit of feed production that can be attributed to these biofuels. However, this domestic market is estimated to become saturated relatively quickly at the rate of construction of ethanol and RME plants now in progress. An estimate is that the total production of ethanol and RME from domestic grain and rape seed corresponding to 3–4 percent of today's consumption of gasoline and diesel oil is possible before the domestic animal feed market is saturated.

Second-generation vehicle biofuel

Ethanol from grain, RME and biogas are often referred to as the first-generation vehicle biofuels. Second-generation vehicle biofuels that are in the course of development are based instead on wood raw material from the forest, energy forest or straw fuels (straw, energy grass) from agriculture. The two benefits of these new fuels are that the energy efficiency of conversion is often higher and that an appreciably greater resource base (forest raw material and energy forest) can be used than for the first-generation fuels. Thermal gasification is used in the production of new fuels such as methanol, dimethyl ether (DME), Fischer Tropsch diesel oil (FT diesel oil) and methane, whereby wood biomass is heated at high pressure. Synthesis gas is then formed and can be converted to various fuels. But the technique is not yet fully developed, and factories of the size of a pulp mill are also needed to achieve low production costs.

Another alternative is to produce ethanol from wood raw material. This technique is not yet fully developed either, and a disadvantage is that the yield of fuel per unit of biomass is lower than for fuel from gasification. But when ethanol is produced from wood raw material, a by-product – lignin – is obtained, which can be used for energy purposes. This by-product can be used for the production of pellets, or for electricity and heat generation. At the present time, ethanol production also requires a cleaner wood raw material than that needed for gasification, and this leads to keener competition with pulpwood for the forestry industry. Both deciduous and coniferous wood can be used, and the two have their advantages and disadvantages. Deciduous wood is easier to decompose by hydrolysis in which the cellulose molecules are split into smaller sugar molecules, but are more difficult to ferment to ethanol, since a large proportion of the sugar molecules consists of pentoses with five carbon atoms. Coniferous wood is more difficult to hydrolyze but is easier to ferment, since it has a large proportion of hexoses (sugar molecules with six carbon atoms).

Figure 4 shows the yield of ethanol, heat, electricity and pellets per hectare of arable land if energy forest (in this case, poplar) is used in different ways. In the five different cases, poplar is used only for ethanol production, only for heat generation, combined heat and power (CHP) generation, and two different biorefinery concepts. In one of these, ethanol, electricity and heat are produced simultaneously, while in the other, ethanol and pellets are produced simultaneously. The figure shows that the total energy yield in one of the biorefinery plants is high, almost as high as the combined district heating and power generation, at the same time as fuel is produced. However, the total amount of fuel produced per hectare is somewhat lower in a biorefinery plant than if only fuel is produced. Since electricity and fuel are regarded as more valuable energy carriers than heat and pellets, it is important not to endeavour to only achieve a high energy yield in a biorefinery plant, but also a high proportion of electricity and vehicle fuel.

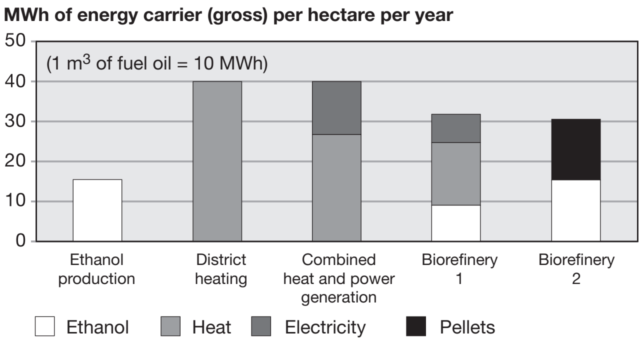


Figure 4. Yield of ethanol, heat, electricity and pellets per hectare of arable land if poplar is used in different ways (cultivation in southern Götaland on average arable land)

Environmental efficiency

The extraction of forest fuel and growing of energy crops can take place without any major negative impact on the local environment. The removal of slash causes nutrient loss, but this can be compensated by recycling the ash after combustion and, if necessary, also by nitrogen addition. Nitrogen fertilization is an effective measure from the energy aspect, since growth of biomass may be up to 50 times higher than the energy input in the production and spreading of the fertilizer. The removal of slash can even lead to reduced risk of nutrient leakage and reduced acidification in southern Sweden. Since the input of diesel oil and other energy is low in forest fuel extraction, the emission of greenhouse gases is also substantially reduced when fossil fuels are replaced. This reduction depends on the fossil fuel that is replaced, how it is replaced and how the bioenergy system is designed.

Cultivation of perennial crops as energy forest and energy grasses normally causes lower environmental impact than growing of annual crops, such as grain and oil plants. If agricultural land is covered all the year round with perennial energy crops, the risk of nutrient leakage and over-fertilization is reduced. The growing of annual crops requires more input energy, and this causes higher emissions of greenhouse gases than when perennial crops are grown. More fertilizer is normally also used for annual crops, which leads to increased emissions of the nitrous oxide greenhouse gas. The total reduction in greenhouse gas emissions, expressed per tonne of biomass, will therefore be higher when perennial energy crops replace fossil fuels than when annual crops do it. The actual reduction per hectare also depends on the harvest level for the various crops.

When residual products such as manure and sugar beet leaves are used for biogas production, high indirect environmental benefits may result, such as reduced risk of nutrient leakage. When manure decomposes to biogas, the emissions of the greenhouse gas methane from traditional manure storage in tanks will also be reduced. This reduced emission of greenhouse gases may be as high as the reduction achieved when biogas replaces fossil fuels. Manure-based biogas can thus lead to "double climate benefit", so to speak, that justifies investment in these systems.

Difficult to generalize

Bioenergy systems can consist of a multitude of different combinations of raw materials, conversion techniques and final fields of application. Depending on the aspects studied and the local conditions, different systems may have their specific advantages and disadvantages. So it is difficult to make far-reaching generalizations and classification into better or poorer bioenergy systems. Detailed analyses would be required for this purpose based on the actual conditions.

Anyone who declares with certainty in the debate on how good or poor bioenergy systems are, without stating at the same time the conditions under which the appraisals are made, either promotes special interests or lacks knowledge. But a conclusion that can be drawn is that forest fuels such as slash, high-yield perennial energy crops such as various forms of energy forest, together with residual products that remain unused today, are usually efficient in terms of resources, energy, the environment and costs.

Moreover, the development of various types of biorefinery concepts appears to be an attractive strategy from the energy and resource viewpoint if they lead to biomass being utilized even more efficiently than when each energy carrier is produced individually. Development of biorefineries is particularly important for being able to produce vehicle fuels with high resource efficiency. New technical solutions may therefore silence today's debate on whether we should generate electricity and heat or vehicle fuel from biomass. The answer will probably be both!

Pål Börjesson is Associate Professor of Environmental and Energy Systems at Lund Technical University. His research is focused on broad, interdisciplinary system studies of bioenergy systems, with focus on how these can be utilized in the best way as regards the environment, energy, resources and costs.

Today's analysis methods create overconfidence in bioenergy

Torbjörn Rydberg analyzes bioenergy systems in a more comprehensive manner than is usual in today's energy analyses, of which he is critical. He also considers the energy that drives people's work, such as food, and the energy that is used but is regarded as free of charge by the economic system, including solar energy. He comes to the conclusion that an industrial society such as ours is today cannot be run with renewable energy. We must cut down our demands on the Earth's resources.

Torbjörn Rydberg, Department of Urban and Rural Development, Swedish University of Agricultural Sciences

How much energy is needed to support a human being? If we measure only the energy used for driving the body, the answer is about 2 500 kilocalories per day. But many forms of energy are converted for producing this food. From a system perspective, energy of the order of 10 kilocalories in the form of fossil fuel is converted for producing 1 kilocalorie of modern packaged food displayed in the store. So the food per person per day has an energy consumption of around 25 000 kilocalories of fossil fuel. But to supply a human being comprehensively in a certain cultural context, an entire lifesustaining system and a number of different energy inputs are needed. The magnitude of these requirements and the consequences they have on the life- sustaining system are largely a matter of the society and the lifestyle we choose to develop.

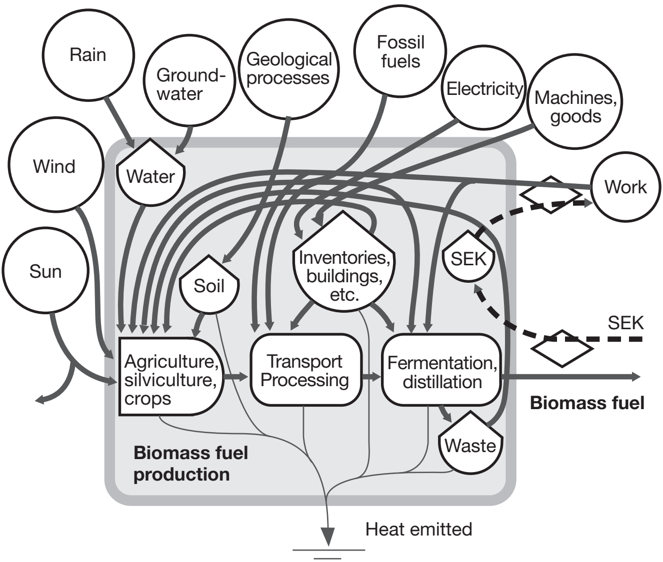
Industrial society was developed with the use of engines, electricity, cables, railway networks, road networks, trade and communications. The fossil oil that enabled us to achieve the rapid industrial growth was easy to find and extract, and relatively free from the admixture of other substances, concentrated, easy to transport and easy to convert to other energy forms. A couple of hundred years later and because fossil fuels are finite and have a negative environmental impact, we are now in a situation in which we must consciously review and change our energy supply and our lifestyle. Would it now be possible to replace the fossil fuels by other fuels from biomass?

With the whole Earth as a system

Biomass fuels are presented in studies as renewable and less environmentally loading substitutes for fossil fuels. The message is easy to accept and believe. But as biomass fuels are studied with a broader system perspective using what is known as *emergy analysis*, it will be found that large quantities of non-renewable energy resources are consumed in the production which causes serious environmental loading. Emergy analysis considers the entire geobiosphere as a system, i.e. the whole Earth, including the crust and the atmosphere. The emergy calculation quantifies the demands, for instance, that a bioenergy system makes on the work processes of the geobiosphere.

If cultivation, further processing, distribution and utilization of an energy resource are to perform as intended, we need information on all forms of energy that must be provided directly from Nature or indirectly via the community. A production process demands a number of different resource qualities and energy forms to perform at all. No buns can be baked merely by heating the oven. All other ingredients must also be provided, including the farmer, appliances and the baker. And neither will there be biomass fuels merely because there is fuel for the tractor on the field and energy for the factories to produce other goods necessary for production.

To "make" wheat or other agricultural crops today demands both renewable energy flows in the form of sun, wind and rain, and non-renewable energy flows in the form of diesel oil, phosphorus and machines. Human work is also needed. There will be no wheat



Many different resources are needed for producing biomass fuels. The evaluation method known as emergy analysis considers all flows.

unless all forms of energy are used simultaneously and their specific energy quality is thereby consumed. Machine parts are worn, the phosphorus in its easily soluble, easily accessible to the plant and spreadble form is consumed, diesel oil is burned, the chemical potential of rain is put to use, parts of the wind energy have been used for transporting water and gases, and parts of solar energy have been consumed directly in photosynthesis. Wheat is a new form of energy that can then be used in various ways, and as energy carrier is converted by means of other energy forms into products such as ethanol as vehicle fuel.

Many different input goods that originate in different ways from the Earth's "network" of processes are thus needed for producing biomass fuels (see the figure that shows ethanol production from wheat as an example).

Sun, wind, water, soil and work

The fact that an emergy analysis of a bioenergy system includes sun, rain, soil and human work is because they are all necessary for the process to produce bioenergy. It is important to include solar energy in the system, since the sun drives energy flows on Earth. Everything that is valuable must be produced and maintained by the working processes of Nature, including photosynthesis. These valuable processes begin with there being solar energy that flows towards the Earth. Virtually all goods and services therefore need solar energy. Since sunlight is a flow-limited resource, i.e. only a certain amount arrives per unit of time, we can see opportunities and limitations of various projects and development strategies in which solar energy is included in the evaluation.

It is important to know the amount of rain falling on a certain area and the utilization of this water if we want to develop systems that are driven by renewable energy. Wind is included in the calculations, since it carries out an amount of work that is free of charge in Nature and we are dependent on this. As part of the life-sustaining system, winds are responsible for the climate, they recirculate water to subsequently produce rain, they move and dilute air pollutants, they assist in eroding soil and producing new soil, and they drive waves and currents in the seas. Our existence and welfare are directly and indirectly dependent on the free-of-charge work of the wind. The rain and winds are driven by, among others, the sun and they are consequently also limited in flow and set limits to what is possible.

Bioenergy systems are dependent on the soil if cultivation is to be possible. The soil is a fundamental condition for bioenergy. It must therefore not be destroyed. Emergy calculations therefore include it in the evaluation of bioenergy systems.

Today's and tomorrow's technology needs people with the competence and ability to work in systems. An emergy analysis includes calculation of the resource requirements for human work, i.e. food and other matter that is characteristic of the social system in which people live in that particular case. Different bioenergy systems in different social systems require people and will continue to do so. But their demands on the surroundings will be different, and by this being clarified, we will have the opportunity to orient ourselves better towards sustainable development for all of us.

Criticism of today's methods

A multitude of natural resources and functions important to life often end up outside the appraisal in today's most widely used evaluation methods for bioenergy systems. This applies to both economic valuation methods and the biophysical methods most widely used today: Energy analyses and Life cycle analyses. As an example, services with which ecosystems provide us end up outside these valuations, since they are regarded in an economic market perspective as free of charge, e.g. sun, wind, rain, fresh water and climate control. And the energy analyses do not take up human work and the supply of various energy forms.

If we only measure the energy resources in calories, joules or kilowatt-hours, we miss the quality aspect of the resources. We miss the fact that different energy forms have different magnitudes of ability to perform mechanical work, although exergy calculations can be carried out. *Exergy* is energy quality, with focus on mechanical work capability. As an example, the water in a hydropower dam has high exergy before it rushes down the waterfall. Electrical energy can drive motors and has higher exergy than heat.

What is even more serious is that today's energy analyses miss all other qualitative aspects of the various forms of energy on which we are dependent. As an example, complex forms of life need functional ecosystems. Moreover, the various energy forms are dependent on one another. Between 4 000 and 5 000 joules in the form of solar energy are needed for producing 1 joule of wood. Many joules in the form of organic material are needed for producing fossil fuels, and large quantities of fossil joules are needed for producing 1 joule of human work. Energy forms thus cannot be added at random, and consideration must be given to their dependence on one another.

Systems with different time scales

Every item of goods has its own need for resources and its own requirements for the length of time and the area needed for it to be produced. Trees need a certain amount of time and a different area to be formed than wheat, for example. Coal and oil are formed on a longer time scale. Other minerals and metals require even more time for them to form. This system dependence must be included in a serious resource and environmental consequence description. This is not the case in the analysis methods used today. They arrive at the conclusion that the production will be a certain amount per hectare per year, although the energy resources applied have totally different space and time scales than the system being studied. As an example, the input of fossil fuels, electricity, phosphorus fertilizer, machines and work are not generated by the system being studied.

The emergy analysis time scale is adjusted so that it will be relevant to the processes being studied or the time framework required by the question. Just like evolution biology is studied with relevant time scales, the forest, for example, should be studied with a time scale that is relevant to it. We must not calculate only the energy in kilowatt-hours or kilojoules that can be extracted when a tree is burned. Once a tree has been felled, it will take a long time for a new tree to grow. The solar energy used during the one hundred years when the tree was growing must therefore also be taken into the calculation. When the tree is then harvested and worked, consideration must be given to machines, fuel and maintenance by people included in the study, since they are essential forms of energy that are used. Separate calculations are made for these inputs, which are then used for the forest systems.

Unreasonable land area requirements

The land area requirement will be unreasonably large if we try to substitute today's fossil fuels with biomass-based energy. As an example of this, we can calculate the production of ethanol from wheat in a Swedish factory in Norrköping, without taking into account any natural resource requirements other than the need for land area on which the wheat is grown. We know that 1 hectare of wheat field produces around 5 tonnes of wheat (grain). In the ethanol factory in Norrköping, 5 tonnes of wheat produce 2 cubic metres of ethanol that corresponds to 12 000 kilowatt-hours (of heat). According to the Agroetanol AB company, the process produces 30 percent net energy. This means that every hectare of wheat produces 3 600 kilowatt-hours of ethanol if the process energy for growing, transport and ethanol production is disregarded.

According to the Swedish Energy Agency, the energy requirements of the transport sector, excluding sea transport, are 92 terawatt-hours. The land area required for replacing the fuel needs of the transport sector with ethanol from wheat will be obtained by dividing 92 terawatt-hours by 3 600 kilowatt-hours. The calculation gives a land area requirement of 25,5 million hectares, which represents more than half of Sweden's land area. If 10 percent of Sweden's automotive fuel requirements were replaced by ethanol from wheat or crops grown in a similar manner, the whole of Sweden's present agricultural land area of around 3 million hectares would be required.

For producing automotive fuel, great expectations are made on other crops, such as willow, and a different conversion technique, such as gasification. These systems extend the promise of substantially reduced land area requirements and hopefully reduced resource demands.

Forest is better than annual crops

If biomass fuels are studied with an expanded system perspective that has the ability to value both the work of Nature and that of humans in the same method, it transpires that cultivated annual crops are a poor raw material. If the forest is used as the raw material, the need for auxiliary energy for producing the end product is reduced. But even though the forest alternatives have a lower need for goods and services produced by the economic system, they still dominate over what Nature produced by itself and "free of charge" in the forest.

Emergy is an expression for all the energy that has been converted in various work processes for achieving an item of goods or a service – a sort of energy memory. Emergy is defined as the quantity of energy of a certain form (usually sun) needed directly and indirectly for producing a flow or a stock of energy or matter. The energy memory is usually expressed in solar emergy joule. To obtain a measure, the ratio is usually worked out of the number of solar emergy joules consumed for making a product and the energy contained in the product itself (solar emergy joules per joule).

The first column in the adjacent table shows how much emergy is needed for every joule generated by a number of different energy sources: gasoline, ethanol, heat for district heating from willow, and heat for district heating from forest harvest residues (slash). For every joule of gasoline, around 66 000 solar emergy joules were required, and for every joule of sugar cane ethanol and maize ethanol, 214 000 and 176 000 solar emergy joules respectively were required. Every joule of heat for district heating produced from willow requires 19 500 solar energy joules, and heat from slash requires 21 650 solar emergy joules per joule. Methanol produced from slash is shown in the study to require 33 600 solar emergy joules per joule.

The second column in the table gives the proportion of non-renewable emergy that can be derived to the production place, i.e. oil source or willow field. Fossil fuels have a high proportion of their emergy from here, and the cultivated crops and forest have a low proportion if they are managed without destroying the systems, e.g. depleting or misappropriating the soil. The third column shows how much of the emergy that is derived via the economic system, including machines, fuel, fertilizer and human work. Most of this is also of a non-renewable nature. Gasoline has 10–27 percent of its total emergy from these flows, ethanol around 90 percent and willow heat 92 percent. Forest heat utilizes 67 percent of its emergy consumption from these resources, and forest methanol around 70 percent. The last column shows the proportion of renewable emergy. This is shown as zero for gasoline, 5–10 percent for ethanol, 8 percent for willow, 33 percent for heat for district heating from the forest, and 30 percent for forest methanol.

Type of fuel	**Solar emergy joule per joule of product**	**Emptying of local stock (% of total emergy)**	**Purchased goods and services (% of total emergy)**	**Renewable emergy (% of total emergy)**
Gasoline	66 000	73–90	10–27	0
Ethanol from sugar cane (Brazil)	214 000	–*	90	10
Ethanol from maize (Italy)	176 000	3	92	5
Heat for district heating from willow (Sweden)	19 500	–*	92	8
Heat for district heating from slash (Sweden)	21 650	–*	67	33
Methanol from slash (Sweden)	33 600	–*	70	30

* No information available. It is usually soil loss of organic material that is identified on growing of crops.

The table shows with a number of examples the needs of the surrounding world for gasoline, ethanol, heat for district heating and methanol to be produced. The results come from studies in which the work of both Nature and humans has been calculated on a common energy base (emergy analysis).

Even though the table gives only a few fragments from emergy studies made on different energy types, a decision-maker will be able to see at a general level what demands the various products make on the surroundings. Ethanol production appears to be a very costly process, with a small proportion of renewable driving forces. Care should therefore be exercised in developing it. Heat generated from willow and slash makes roughly the same total energy demands on the surroundings, although the recipes are different. More renewable driving forces are used for heat from slash than from willow. Since forest already exists, heat from slash is probably better than heat from willow. Methanol from slash appears to be an efficient conversion process, but note that the highest proportion is produced with non-renewable driving forces.

Renewable energy is scattered around the landscape

In an industrial society, we are accustomed to having access to energy sources that make modest demands on "harvesting" them, and where the harvested products are highly refined as high-quality fuel, such as oil and fossil gas (natural gas). If we want to have more of them, we can do that since they are available in stock and are thereby not limited in their flow. The more we extract, the more we receive. With better technique, we could extract more and quicker. All we need is bigger and more powerful "pumps". The limitation lies in the magnitude of the stock.

Renewable energy such as sun, wind, water and biomass are more scattered in the countryside. Solar energy is most scattered, followed by wind, water and various forms of biomass that, in turn, can be ranked according to their age. The longer a forest is left untouched to build up its stock of wood, the easier it will be to obtain a large and usable harvest from it and the larger the harvest will be. If emergy analysis is used for analyzing the electricity generated by means of solar cells, it will be clear that it requires a great deal of resources – large amounts must be invested in apparatus and service. The figures for electricity generated by wind turbines and hydropower are much better. An important reason is that Nature has already concentrated the energy flows before we apply our energy-harvesting equipment, and that these working processes take place at higher efficiency than the solutions we have developed so far. But a typical feature of these energy types is also that there is a limited flow of energy per unit of time. No more solar light will impinge on a certain area even if we "pump" more, and no more rain and wind will come.

New view on the planet

Our modern social system is organized to use concentrated fossil energy. Such a society cannot be driven entirely by energy that is as diluted as solar light and biomass. There is no doubt that fossil fuels must be phased out and replaced to some extent by other energy forms. We must put a hard brake on our consumption of fossil fuels and all other energy consumption. But there is no simple alternative.

The complex interaction in the geobiosphere requires a totally new view on ourselves and our planet. It involves cooperation that leads to development that is of benefit to both humans and Nature. Only then will sustainability in the system improve. One of the elements needed for this is knowledge. This does not relate to the quickest and most effective way of emptying the resources of Nature. We are in a situation in which we understand that we are facing a future that not only involves a shortage of fossil fuels, but that natural resources will be affected more generally and that a shortage of more than merely fossil energy will arise.

It is therefore high time we reviewed the evaluation methods we use when taking decisions on our future energy supply. Methodology is available today that is able, on stable natural science grounds, to measure and value the demands that various production processes make on the entire biosphere. Emergy analysis calculations concern sustainability aspects of human activities, and provide valuable information for planning and decision making. But the methods have never been used as a basis for strategic discussions on future energy supply in Sweden. The results available appear to be difficult to accept and interpret, since they are perhaps not entirely compatible with the belief in continual material growth and increased yields in forestry and agriculture.

There is no shortage of energy as it is defined in books on physics, and there is no shortage of willingness to develop new technical solutions. When society is forced to replace the concentrated stored resources by unconcentrated, flow-limited energy resources, we will be obliged to handle all of these different energy qualities and their demands on the surroundings. If the methods do not shed light on this, it will be a problem, as I see it, for the future and the possibilities we have to solve the energy issue.

Food more important than spirits for cars

The demands on Nature will increase substantially if we are to switch from fossil fuels to bioenergy. The land area demands for this substitution will be gigantic. We can already see how people are losing their forests and access to their land merely because fuel is to be cultivated for export. The land available is insufficient. In many places out in the world, it is more important to produce food than to cultivate ethanol for environmentally labelled cars in Sweden.

Annual agricultural crops perform well as food or animal feed due to their specific qualities in the form of usable carbohydrates, proteins, fats, antioxidants, and so on. Using such crops for heat and fuel is very wasteful. The forest gives better figures, but the systems need to be developed so that they will be even more self-sustaining.

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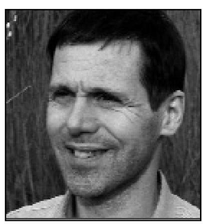
Analyses of bioenergy systems – why do they produce different answers?

Which types of energy system are "best"? To answer to the question, researchers use various methods for analyzing the systems. But even if they analyze a given energy system, they seldom arrive at unequivocal answers. The fact that the debate is sometimes overheated and the source information is contradictory does not make matters simpler for our decision-makers, writes Theo Verwijst. So how should we set about to arrive at clear and unanimous answers that lead appropriately to the development of the energy systems we want?



Theo Verwijst, Crop Production Ecology,
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Many different voices are heard in today's public debate on present and future energy systems, although they all appear to be unanimous about one thing: that a system based on fossil fuels is unsustainable in the long term and that we need to make great efforts to develop alternative energy systems as quickly as possible. But the same persons are not at all agreed on what alternative systems should be employed. The reason for the wide discrepancy is three-fold. In the first place, there are several different system analysis methods that produce varying answers due to varying methodology. The analysis methods can be said to produce different answers because they actually shed light on different aspects of the same question.

In the second place, we should bear in mind that many analyses are made by groups of interested parties with strong special interests, and the methodology and subsystems can then be selected in such a manner that they produce the required results. In the third place, a large part of the debate is run by those who do not carry out the system analyses, but by groups that, perfectly legitimately, have views on the basis of other relevant social perspectives.

If researchers could agree on the ranking of the various systems according to some form of effectiveness measure, for instance, society and politicians would very probably not choose the most effective system. Large-scale introduction of new systems affects the environment, landscape planning, interaction between town and country, the entire infrastructure, and our way of travelling and thereby our personal lifestyles. In other words, the political choice between various alternatives is made not only on the basis of biogeophysical realities, but also on the basis of sociocultural valuations. It would therefore be strange if we were all agreed on the way in which development should be pursued. On the other hand, it is essential for researchers to cooperate by constructively comparing the grounds for different opinions while using scientifically objective yardsticks, possibly to conclude that they are in better agreement on energy system issues than they appear to be today.

Many ways of analyzing

There is a multitude of system analysis methods now also applied to bioenergy systems. Some of the methods have been developed for analyses of subsystems, while others include the entire biosphere, with a time scale of millions of years. These methods differ as regards the volume of information needed for performing the analysis, in their practical applicability and implementability, in their jargon and also in their conformance to biogeophysical and economic realities.

I will discuss briefly energy analysis, exergy analysis and life cycle analysis (LCA), and then conclude with a more comprehensive description of emergy analysis.

There are several other important system analysis methods (environmental consequence description, ecological footprint, cost/benefit analysis, integrated assessment modelling and others), but I have chosen to take as the point of departure those that have a strong linkage to thermodynamics, with the addition of LCA. Whereas energy analysis, exergy analysis and life cycle analysis are frequently used for obtaining the basis for decision processes, emergy analysis is still outside the decision-maker arena. In view of the ability of emergy analysis to shed light, in a fundamental manner, on sustainability aspects that are becoming increasingly important in our planning work, we should consider what would be needed for being able to include this methodology in the work of creating relevant decision information for selecting energy systems.

Energy analysis

An energy analysis is basically an energy balance calculation that can be made on a given energy system or parts thereof, e.g. on plant production from soil preparation up to and including the harvest. An example is given by Pål Börjesson (Figure 2 on page 137). If we take a closer look at willow in this figure, we will see that the energy input is 5 percent of the gross harvest, which means that we apply one unit of energy to obtain 20 units of energy. An important condition for such an analysis is that all components are specified (in this case, diesel oil, machines, spare parts, mineral fertilizer, pesticides, and so on), and that a recalculation is done for every component to the same form of energy (in this case, primary energy) that is also used for the outgoing component. The energy used for the 50 km road transport has also been included in the example.

Compared to emergy analysis, an energy analysis is relatively easy to perform and, above all, needs no controversial data information. However, many of today's energy analyses go far beyond an energy balance calculation and are thus more complicated, but also very useful in broader contexts. These specific calculations can be perceived as crosses between energy analyses (that begin with an energy balance calculation) and life cycle analyses, since they include certain material flows (see, for example, Leif Gustavsson's figure on page 120). Comparative analyses are easy to interpret, provided that there are defined and comparable system boundaries and clearly defined parts for which conversion losses and energy supplied are quantified. This is exemplified very well in Leif Gustavsson's figure on page 115, which shows, for a long succession of subsystems, the inputs in the form of diesel oil and electrical energy, and losses in the form of heat conversion and decomposition of wood.

On the global arena, expanded energy analyses have undergone robust development. This applies in particular to the methodology used for calculating the emissions of greenhouse gases on comparisons of bioenergy systems and fossil-based energy systems. Energy analysis in combination with carbon flow analysis therefore make a great impact in the Kyoto Protocol and in the development of various mechanisms for reducing the emission of greenhouse gases.

Exergy analysis

An exergy analysis is structured in the same manner as an energy analysis, although light is shed in it on losses of energy quality. A definition of exergy is the energy that can be obtained from a system if it is reversibly brought into equilibrium with its surroundings. Exergy is thereby a measure of the usable energy, and it is a quantity that is consumed. Electricity is a form of energy with high exergy value, whereas heat has a low exergy value.

The system to be analyzed is structured in the same manner as in an energy analysis, and the incoming and outgoing flow of exergy is then calculated by multiplying the incoming and outgoing flows of energy by an energy quality factor. Since exergy is consumed, an exergy analysis is highly focused on resource utilization. Exergy analysis is more complex than energy analysis but, if the system is analyzed with regard to resource utilization, it can clarify the physical potential of improving the efficiency of an energy system and determining the potential in the various parts of the energy system.

Life cycle analysis

To some extent, life cycle analysis (LCA) is a much broader analysis method than energy analysis and exergy analysis. The aim is to quantify the environmental effects of a product or service throughout its life cycle - "from cradle to grave". When LCA is applied to technical systems, the aim is usually to quantify the potential environmental impact of the system. Extraction or growing of the raw material, harvesting, distribution, use, reuse and final management of the residual products are included. An LCA can obviously also include the energy perspective, although the emphasis is usually on material flows. The LCA is well suited for comparing alternative products with conventional production systems.

The international standardization organization ISO has developed a standard for life cycle analysis (the ISO 14040 series) that specifies four phases in an iterative process: Goal and scope, Inventory analysis, Environmental impact, and Interpretation. For a given quantity of a product, the analysis results in a list of various (natural) resources that are consumed (e.g. oil) and a list of "residual products" (such as carbon dioxide) that are emitted to the atmosphere, soil and water. These emission quantities then serve as a basis for calculating the effects on the environment, such as acidification and greenhouse effect.

Environmental consequence description

Alongside expanded energy analyses and life cycle analyses, there are other methods (in addition to emergy analysis) that should be taken into account when developing an analytical system for being able to deal with environmental aspects. The environmental consequence description (ECD) is a practical application of a combination of many methods and "the aim of an environmental consequence description is to identify and describe the direct and indirect effects that a planned activity or action may have on people, animals, plants, soil, water, air, climate, landscape and cultural environment, and also on the conservation of soil, water and the physical environment in general, as well as other conservation of materials, raw materials and energy. Moreover, the aim is to allow for a collective assessment of these effects on human health and the environment" (Environmental Code, 1998:808, Chapter 6, Paragraph 3). The ECD is thus an integrated "toolbox" that contains many parts of the earlier energy system analytical tools.

Emergy analysis

Emergy is defined as the sum of all energy of a specified type needed to produce an item of goods, a service or a fuel. This cumulative energy is expressed in solar equivalents or solar emergy joule (sej). Simply expressed, the emergy of a product or service represents the amount of energy that would be needed if only solar energy were used to produce the product or service. Emergy can thereby be perceived as a memory in which all energy needed for producing the energy in the product or service has been added. This means that all inputs leading to the product or service are included, and that a given product can have different emergy values, depending on the processes that led to the production of the product. The cumulative energy can include both contributions from the human economic system as work and synthetic material, and input from Nature, such as sun, water, wind and "natural" materials.

The emergy theory (that Torbjörn Rydberg writes about in this chapter) has its roots in an extensive ecosystem theory work. A part of the theory serves as a base for fundamental hypotheses on the role of energy conservation to the survival and development of biological systems. This means that emergy analysis is based on a concept that comprises the entire biosphere and may include a time scale that geologists – but not business or political economists – are accustomed to dealing with. Due to its long development in scientific ecological circles, the emergy analysis culture is characterized by definitions, linguistics and terminology that are fairly alien to energy engineers and economists. Part of the confusion in today's debate can be ascribed to the terminology that is very specific to the subject.

Both ecology and economy

Emergy analysis gives an interesting perspective since it covers both ecological and socioeconomic processes. Emergy analysis has been advanced with the argument that it represents energy grounds for quantifying and valuing all products and services, regardless of whether they come from Nature or from human economy. This is done by using the transformity concept that corresponds to the amount of solar energy that would be needed for every service or product to obtain one joule (J) from the service or product. This is a measure of the emergy intensity (sej/J) or material-specific emergy (sej/g). By carrying out an emergy analysis for an entire economic system, the amount of emergy that supports the monetary flow in the economic system can be calculated. Transformity for the money in an economic system for a specific year is then expressed in sej/currency. The transformity (τ) for a product is defined as emergy (M) divided by the available energy in the system or product (B):

$\tau = M/B$

Even if the exact values of transformity can be discussed, the concept is usable and does not usually significantly affect the results of most emergy analyses.

Available energy

A fair number of ordinary physicists have problems with the fundamental physics in emergy analysis. It is sometimes claimed that emergy analysis is not scientific, since one of the cornerstones in the theory cannot be proven. This refers to what has been called the fourth law of thermodynamics ("the maximum empower principle") which says that all self-organizing systems endeavour to maximize emergy utilization. If there is the will – as it is among many emergy analysts today – to take the principle as a hypothesis that ought to be researched into, this unproven hypothesis represents no grounds for rejecting emergy analysis as scientific methodology.

One of the traditionally weaker sides of emergy analysis methodology is that there is a great deal of confusion and also some doubts regarding the relationship of emergy to traditional and established thermodynamic concepts. Questions remain concerning the concept of "available energy" (B in the above equation). Under certain circumstances, "available energy" coincides with the concept of exergy. The absence of a formally defined relationship between the concepts of emergy and exergy makes it difficult for various branches of system science to communicate with and understand one another in fundamental assumptions. Some work has been done in recent times for dealing with this shortcoming.

Stringent interpretation necessary

Emergy analysis is claimed to be ecocentric instead of anthropocentric, and is considered to be able to assign to Nature the value it deserves. We end up here in a scientific philosophy dilemma that demands taking a stand. It can be denied that something has a value unless Man has explicitly assigned a value to the relevant object. For anyone who has been captivated at some time by a beautiful flower and claims to have experienced a value far beyond the energy value or market value of this insignificant quantity of biomass, it is customary to refer to an "inherent" value. The problem with this valuation is that it cannot be made on the basis of a subject/object relationship, and thereby ends up outside the scientific domain.

It is important that an emergy analysis carried out in a natural scientific manner be followed by a stringent interpretation in the same spirit, since it would otherwise be associated with natural romanticism that makes it difficult to use its results as a basis for important decisions in society.

System demarcation

System demarcations of emergy analysis in relation to the demarcations made in other types of analysis lead to difficulties in many comparative interpretations of results. From an emergy analysis perspective, it is claimed that other methods exclude part of the information essential to the calculation, whereas it can be considered on the basis of other methodology that emergy analysis takes up matters (on the cost side) that are not relevant, which then makes the analysis more difficult and complicated.

Emergy analysis leaves no space for "free-of-charge services" from Nature or for excluding their "costs" that exist, regardless of whether or not we use these services. In the question of system demarcation, it is difficult for different schools to understand one another's fundamental assumptions.

Different perspectives on the same energy system

In view of the differences in fundamental assumptions, underlying philosophy, method of approach and also goals, it is fairly obvious that the various system analysis methods mentioned above give different perspectives on the same energy system, and it is clear that their results are not directly comparable with one another. But there is scope for learning from one another's methods, particularly if we approach one another with openness and in a spirit of scientific inquisitiveness.

It is sometimes claimed from an emergy analysis perspective that the "correct" value of a service or product can be given. This is true if we mean that a common denominator can be found (sej) for comparing and quantifying different services or products. We must remember that the result of the methodology is an attempt to quantify, not to value. If we forget this, we will be confronted with a psychological problem, judging by the many critical reactions to emergy analysis. As shown here, there are many other scientifically defined ways of quantifying and ranking systems, and the methods are, by definition, no less right or wrong than emergy analysis. And as in the case of quantification methodology, we can ask the question whether it is practically possible to develop an empirical basis with sufficient precision so that it will be usable to decision makers, particularly in a changing world with rapid technological development.

I stated by way of introduction that energy, exergy and life cycle analyses are frequently used for obtaining decision information, whereas emergy analysis is still of a more academic nature. Life cycle analysis, which is a young method compared to emergy analysis, has been affected in its development by many good ideas from both energy and emergy analysis schools. But as long as there are uncertainties concerning the emergy concept in relation to established thermodynamic concepts, the emergy concept is an exciting research area, but not an acknowledged methodology on which political decisions can be based. Within circles that are engaged globally on "integrated assessment methods", there is a strong awareness that all methodological elements in such assessments must be scientifically acknowledged in broader circles. As soon as there are uncertainties, there will be obstacles in many political and strategic decision processes.

It is not impossible that research advances that have recently been made regarding the formal relationship between emergy and conventional thermodynamic concepts can gain such a foothold in the emergy debate that it will attract a much broader scientific circle. In my opinion, the methodology will then be "recognized". This is not the case today, and it will therefore be questioned as decision information in important decision processes.

How about the future?

It is inherently a great challenge to endeavour to understand why the various methods give such different perspectives on a given system, but it is essential if we are to be able to weigh together these important perspectives in order to arrive at a well-founded decision as regards choice of energy system. So great responsibility rests on all system analysis researchers to endeavour to understand one another's methodology, to review critically both their own methodology and that of others, and to present it pedagogically and in a scientifically well-founded manner.

Bioenergy will not solve the whole of our energy problem. On the other hand, we have a superb bioenergy potential in Sweden, and by applying different system analysis methods, we will be able to utilize it more optimally and efficiently. In addition, the analyses will assist us in improving the way we give consideration to the environment on which we are dependent for our well-being and our survival.

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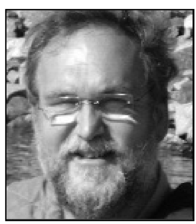
Gasification of biomass – from producer gas to synthesis gas

Gasification of biomass is a blend of old and new technology which is predicted to have a dazzling future. Many different solid biofuels can be used, the technology is usable on both a large and small scale, and its level of efficiency is high for large systems. The synthesis gas produced is a key raw material for the production of second-generation automotive biofuels. Advanced gasification technology is also a key technology for a possible hydrogen-based society geared around biomass as an energy resource, writes Erik Rensfelt.



Erik Rensfelt, ERen Energy

Biofuel in the form of wood for cooking and heating belongs to mankind's earliest development. In our cold climate, firewood has always been important for households. The 1960s, when oil was extremely inexpensive, were an exception. Nowadays, we can again see large woodpiles at many homes in rural districts and in smaller communities.

Particularly in the Nordic region, thermal treatment other than incineration has played a crucial historic role. The reasons for early forestry and replanting in Sweden are to be found in the threat of a shortage of trees that had been posed by early exports of tar and charcoal. In the first years of the nineteenth century, some 137 000 barrels of tar were exported. Charcoal was produced in charcoal piles and later in closed heated kilns. Tar and other chemicals were able to be extracted from the condensate that formed when the gases cooled.

From the mid-1800s, sawn wood products took over as leading export goods from the forestry sector, followed by paper pulp as from 1920. The pulp industry also supplies chemical by-products such as tall oil (fatty acids) and ethanol. These by-products formed the basis for Sweden's organic chemicals industry and accounted for the bulk of the supply of such chemicals in Sweden during the Second World War. During that war, the gasification of charcoal and later also of wooden blocks played a major role as a petrol substitute in the form of producer gas. The gas was produced in small air-blown gasifiers on or behind the vehicle. Owing to their substantial heat losses and simple design, the efficiency of these producer gas units was poor, approximately 60 percent. Water and particulates were separated off by cooling and filtration before gas and air were drawn into carburetor engines which were, by today's standards, very simple. In Sweden alone, around 50 000 vehicles used to run on producer gas.

Research on gasification

After the oil crisis in 1973, a certain amount of research on gasification was initiated at the Royal Institute of Technology in Stockholm. The oil crisis in 1978, with substantially higher oil price rises in absolute terms than in 1973, led not only to broader research and development but also to a certain degree of commercialization. In the first half of the 1980s, a couple of gasifiers (Bioneer shaft furnaces) were built to supply heat to Lid and Vilhelmina, and also several gasifiers (CFB) for lime sludge ovens in the pulp industry in Karlsborg, Värö and Norrsundet. Most are still in operation. A significant development program for fuels was conducted in the 1980s, chiefly for methanol from biomass. This early development was halted by falling oil prices and a lack of State perseverance.

The commercialization of gasification technology was delayed despite a certain amount of development work taking place in the 1990s. For alternative fuels, development within the EU and Sweden came to be governed more by considerations of agricultural policy than by scope for long-term competitiveness and energy efficiency. It was not until the impact of climate issues in the last few years and, to an even greater extent, the rising oil prices over the period 2004–2005 that biomass gasification has again come to take centre stage.

Dry distillation has become pyrolysis

Heating fuels in an oxygen-free atmosphere used to be called dry distillation. Many people can no doubt remember school chemistry experiments in which a test tube of wood fragments was heated to form charcoal, tar water and combustible gases which filled the test tube and could be ignited in the opening (Figure 1). This was the principle underlying dry distillation. The process is now called pyrolysis. After cooling, the products from pyrolysis are a solid carbon-rich residue (carbon/coke/char), liquid hydrocarbons (tar, tar water) and gases such as carbon dioxide, carbon monoxide, hydrogen and methane. By controlling temperature, pressure, particle size, rate of heating and retention time, the yield can be varied to obtain 10–40 percent char, 20–80 percent gas and 5–70 percent tar and tar water (biooil).

If these products are burned, they react further with oxygen in air to form water vapor and carbon dioxide, and the energy is released as heat which is transferred directly to the surroundings or indirectly to water or water vapor. In gasification, the aim is to bind as much as possible of the fuel's energy in the gas as a pure and easy-to-handle energy carrier, which can then be used not only in efficient machinery such as engines and gas turbines for electricity generation but also to chemically synthesize fuels such as methanol, petrol or diesel. In practice, every combustion or gasification process is initiated with heating of the fuel under the protection of the gases evolved, i.e. pyrolysis; this is then followed by further reactions of the primary products.

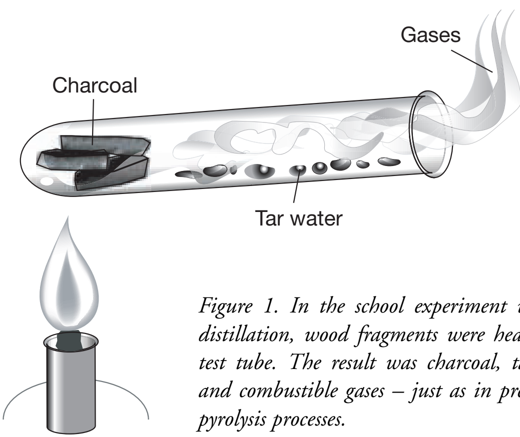


Figure 1. In the school experiment with dry distillation, wood fragments were heated in a test tube. The result was charcoal, tar water and combustible gases – just as in present-day pyrolysis processes.

Gasification means that, after pyrolysis, the primary products react further with water vapor, carbon dioxide or via incomplete combustion with oxygen/air to form energy-rich gases such as hydrogen, carbon monoxide and methane. Both the pyrolysis and the reaction of the charcoal with water vapor or carbon dioxide require heat, i.e. heat must be supplied. This takes place either directly via partial combustion with air/oxygen or indirectly via a hot surface or with heat carriers. Gasification of charcoal requires more than 800 °C to take place with reasonable speed. The production of a pure tar-free gas requires more than 1100 °C thermally and over 850 °C with the aid of catalysts. Gasifiers therefore usually work at temperatures above 850 °C.

Many solid biofuels can be gasified

Gasification processes can use many types of solid biofuels and other organic material such as peat, coal, waste and wood (including bark and needles or leaves). The gasification processes are not particularly sensitive to fuel composition. Moisture content and to a certain extent ash content and ash characteristics are very important for the process. The moisture content is in many cases approximately 50 percent, and is reduced by drying prior to gasification. The drying process can take place with low-grade waste heat, thus boosting total efficiency.

If the fuel contains pollutants such as chlorine, nitrogen or sulfur, this can be removed by purification stages during or after the gasification process. It is therefore possible to use waste and other waste products as raw material. Major development efforts have been made since the 1960s in relation to the gasification of waste, but a broad commercial breakthrough has not yet been achieved. Waste is a fuel subject to many process difficulties, including variable composition.

From very small to very large

'Gasification processes' is a generic term for technology which assumes different forms chiefly depending on the fuel raw material, size and application. The technology ranges from small producer gas units for motor operation in India to gasifiers for fuel gas in lime sludge ovens used in the pulp industry and pressurized synthesis gas processes for fuel production. The process design on each scale or application is determined by the technical requirements, primarily the least expensive ways of meeting the requirements (Figure 2).

Small-scale producer gas processes must use very inexpensive equipment with a significant element of manual servicing. Recently, they have mainly been developed in India for various agrofuels down to an extremely small scale with an output of 5 kilowatts. The gas is produced by partial oxidation with air and fuel in a parallel flow from the top in a fixed bed. The

The size governs the choice of gasifier (fuel power in megawatts, MW)

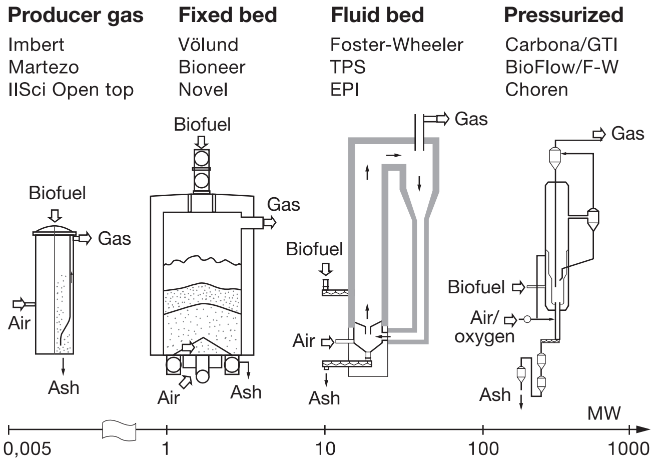


Figure 2. Gasification processes are used on different scales, with different fuels and for different purposes – from small producer gas units to pressurized gasification for liquid fuel production.

technology therefore becomes highly fuel-specific and dependent on particle size. Engines of up to several hundred kilowatts can be operated with this technology. Modern turbocharged engines make great demands of tar- and particulate-free gas; ever more refined purification stages are therefore required.

For larger scales, 1–10 megawatts, up-draft shaft ovens or fixed-bed gasifiers are preferable. The water vapor-saturated air is blown in at the bottom and the fuel is fed in from the top. Modern variants have been developed in Finland, Denmark and Canada and are also in operation in Sweden. The technology, which traditionally yields high tar contents, has been further developed in Finland and Denmark into multistage processes with thermal or catalytic tar decomposition and gas purification in filters for the operation of larger engines on a megawatt scale.

As many fuels are difficult to break down into fine power and often have varying particle sizes, considerable efforts have been made to develop fluid bed processes that can accept such fuel. Air, oxygen or water vapor is blown into a sand bed and the sand is allowed to swirl around. The fuel is fed into the heated sand bed and gasified rapidly. At high gas velocities, the sand also blows out of the gasifier, but is returned continuously via a cyclone and a downpipe to the gasifier in a circulating fluidized bed (CFB). This type of gasifier was built for the forestry industry's lime sludge ovens in Sweden and Finland over the period 1980–85, when oil prices were high. Some of them are still in operation. CFB combustion technology has carved out an extensive market for itself in relation to fuel-flexible boilers for coal, peat and biomass on a scale of 10–500 MW fuel. In this case, air is added in excess to achieve complete combustion.

If the gas is to be used at high pressure, as in the synthesis of hydrocarbons, pressurized processes are to be preferred. Processes with indirect heat supply and gasification with steam have been developed in some cases and with the greatest success by Repotec in Austria with a demonstration plant in Gussingen for engine operation and combined heat and power production. The motor application has shown a high level of availability, but the costs are still high compared with conventional steam technology.

Gasification technology for heat

For the production of heat in applications that require a clean environment, such as ovens in the glass and metal industries, biomass gasification can be an alternative. The simplest air-blown gasifiers yield a low calorific value for the gas due to the fact that the nitrogen in the air dilutes the gas and gives it a nitrogen content of approximately 50 percent. They are therefore unsuitable for supplying heat at temperatures above 1200 °C. This calls for indirect or oxygen-blown gasifiers that provide better gas quality. Up to now, such gasifiers have been unable to compete with liquid fossil fuels.

For heat applications within the housing sector and most other heating sectors, combustion technology represents a good alternative, and gasification technology may therefore play only a marginal role.

Gasification for power production

For small-scale power and combined heat and power production, gasification/engines yield somewhat better efficiency than combustion/boilers/steam turbines. Significant development work has been put into power production on a scale of between 5 kilowatts and 5 megawatts. Gas purification has often been a problem, but new technology is now available that solves the problem, such as washing with organic solvents or catalytic tar cracking. A number of demonstration plants are in service or are being taken into service during 2007 in Finland, Denmark and Austria. To date, high costs compared with conventional combustion and steam technology have been limiting factors.

On a larger scale, use of the gas in a combined cycle known as IGCC (Integrated Gasification Combined Cycle) gives high levels of efficiency for electricity. (An IGCC has both gas turbines and steam turbines; this means that the gasified fuel and water vapor formed from the heat from the combustion process each passes through a turbine.) Such technology has been developed in Sweden by TPS (TPS Termiska Processer AB) and Sydkraft/Foster-Wheeler up to demonstration scale. Commercially, this BIGCC (Biomass-IGCC) technology has not yet been able to compete successfully against conventional combustion and steam technology. Improved gas turbines may end up boosting the competitiveness of BIGCC technology over time.

The factor that is crucial to profitable power production with biomass is not primarily the choice of combustion or gasification but rather the scope for combined heat and power production, i.e. simultaneous production of electricity and heat for industry or district heating. BIGCC may yield up to twice the electricity output for a given thermal load as conventional steam technology, but this comes at the expense of somewhat lower total efficiency and, to date, higher costs. If electricity from biomass comes to have a significantly higher price than heat from biomass, this may lead to the BIGCC technology being commercialized.

Synthesis gas: a key raw material for liquid fuel and chemicals

To produce liquid fuel from biomass effectively, synthesis gas (hydrogen and carbon monoxide) without pollutants must first be produced (Figure 3). Synthesis gas offers many commercial openings for making chemicals and liquid fuel. The processes for making synthesis gas from biomass are thus key technologies in this context. A few such technologies are currently at the pilot or demonstration stage and still call for scaling-up and technical and commercial demonstration.

Most relevant synthesis processes (which synthesize chemicals from synthesis gas) work with catalysts under pressure. The gas must be very clean of pollutants such as sulfur and chlorine in order not to poison the catalyst.

A number of synthesis processes exhibit relatively low conversion on passing through the catalyst, and recirculation of the synthesis gas is therefore often required. This means that the proportion of non-reacting (inert) gases must be kept very low, at a few percent in the synthesis gas. This requirement means that, after the gasification stage, there are a number of purification and washing steps before the synthesis gas is compressed in the synthesis process.

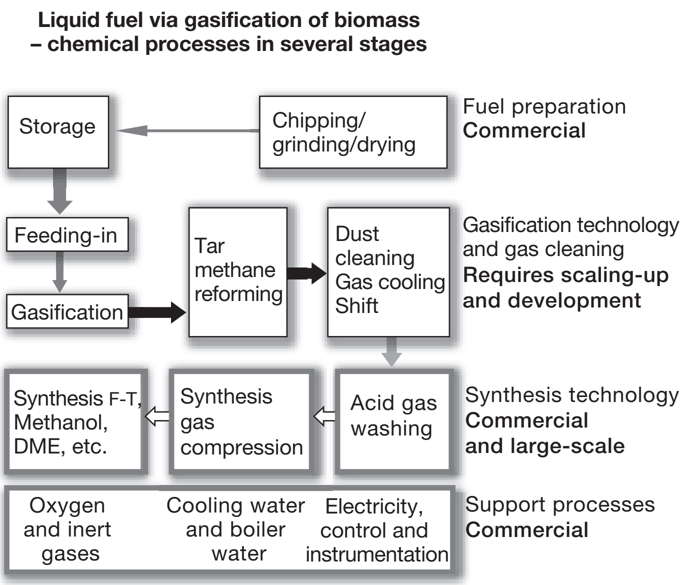


Figure 3. The process from biofuels to synthesis gas and the manufacture of liquid fuels comprises a long series of chemical processes. To be effective, it must take place in large plants with capacities of several hundred megawatts.

The entire process from the biomass stage thus comprises a long chain of processes which, to achieve high efficiency and reasonable costs, must be carried out in large-scale plants with capacities of several hundred megawatts of fuel.

The requirements concerning the gas and the large scale mean that the gasification process should be carried out at high pressure and with oxygen as the gasification medium. The most advanced biomass process at the present time is a German process, Choren, which is now built into a demonstration plant for Fischer/Tropsch hydrocarbons on a scale of 45 megawatts of fuel, and which is planned to be taken into service by 2007. Fischer/Tropsch synthesis was developed in Germany before the Second World War and means that hydrocarbons can be formed over iron or cobalt catalysts at high pressure and moderate temperature. The Choren gasification technology comprises a pyrolysis stage, a high-temperature stage and a reducing stage with char.

In Värnamo in Småland in southern Sweden, work is being carried out to modify an existing demonstration plant for BIGCC to synthesis gas production on a scale of 20 megawatts fuel in an oxygen-blown pressurized fluid bed with a catalytic reforming stage, known as Chrisgas technology. The crucial decisions on this are expected during 2007, with operations set to start in 2009.

A number of projects in Finland, Germany and Japan are currently carried out on a smaller scale with a view to being scaled up to demonstration scale in a few years' time. Unpressurized indirectly heated CFB technology, which has been successfully developed for engine operation on a scale of 8 megawatts in Gussing (Austria), can also yield synthesis gas. In my view, it is unsuitable for the large scale required for fuel plants.

Gasification can remove carbon dioxide from the ecocycle

Gasification allows far-reaching purification of the fuel/gas prior to final combustion or chemical synthesis. This boosts the competitiveness of gasification at a time when environmental requirements are being tightened up for electricity and heat production. This applies not only to conventional environmentally disturbing pollutants but also to climatically disturbing gases, mainly carbon dioxide. In gasification processes, it is possible to take out most of the carbon dioxide before combustion, and ultimately only hydrogen can be burned after purification and conversion. The carbon atoms are converted first to carbon monoxide in the gasifier and then to carbon dioxide via the addition of water and catalyst. If this is done in several stages, all the carbon monoxide can be eliminated, forming hydrogen which then bears the energy that was present in the carbon monoxide.

If biomass is used in this way, not only does the process become carbon dioxide-neutral but it even removes climate gases from the ecocycle provided that the carbon dioxide can be deposited at sea or on the earth's crust. Carbon dioxide removal is also being developed for combustion processes, but is not yet commercially available.

Rapid expansion

Fuel flexibility and the possibility of high levels of efficiency in vehicle fuel production mean that gasification technology and the synthesis approach may make significant future contributions to the supply of fuels. The potential for liquid fuels via gasification is determined first of all by the level of development of the technology and the time needed for scaling-up and commercial demonstration. My view is that gasification technology may grow rapidly until 2020 (Figure 4). The gasification technologies for black liquor (in the pulp industry) and biomass have twice the efficiency for liquid fuel (50–60 percent) as hydrolysis and fermentation of wood to ethanol, a method that is currently being developed. With a similar expansion in tonnes of fuel, liquid fuel production thus becomes greater via gasification. In the longer term, the ceiling is determined by competition for land and raw materials for food, fibers, etc.

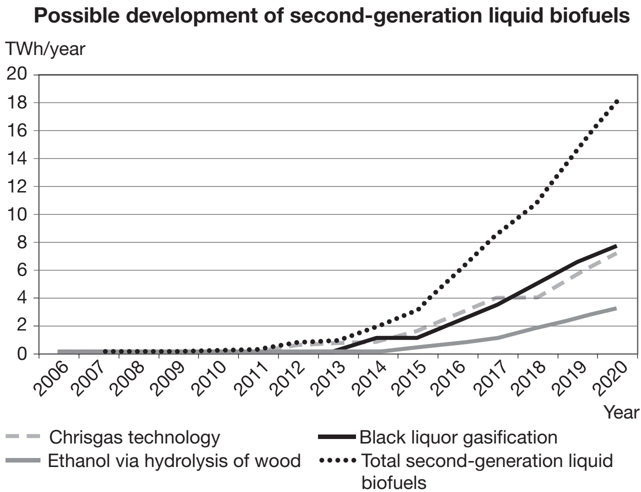


Figure 4. It is possible that second-generation fuels will expand rapidly until 2020 so that they contribute approximately 18 terawatt hours per year.

For effective liquid fuel production, advanced gasification is a key technology for most future options – from synthesis of diesel and petrol to future fuels such as methanol and DME and a possible hydrogen-based society geared around biomass as an energy resource. If vigorous commercialization of gasification technology for liquid fuels takes place, other applications will be carried in its wake, chiefly power production in a combined cycle. The technology will become cheaper, more effective and more reliable once a number of plants have been built.

The environmental and effectiveness requirements in combination with the finite nature and spiraling cost of oil are leading to gasification technology for biofuel again becoming a crucial technology in both Sweden and the rest of the world, as a key part of a sustainable society.

Erik Rensfelt was involved in the 1970s in starting the Gasification project at the Royal Institute of Technology in Stockholm and was its project manager for five years. The research results were scaled up to a pilot plant in Studsvik over the period 1981–86 for synthesis gas from biomass. These results are now being incorporated in the demonstration plant based on Chrisgas technology at Värnamo in southern Sweden. During 1992–2000, TPS in Studsvik developed, under Erik's direction, CFB gasification and built plants in Italy and England. Erik has participated for many years in working groups within the EU, including the Directorate-General for Research. Since 2005, he has been a freelance consultant specializing in biofuel.

Biogas – can a little become a lot?

The biogas process provides three useful things: waste treatment, energy and fertilizer. Currently, Sweden produces only 1.3 TWh biogas every year, barely one half of which is produced in municipal sewage treatment works. The technical potential is between 10 and 20 TWh, and 80 percent of the raw product can come from agriculture. If the potential is to be exploited, various players must collaborate more effectively, writes Åke Nordberg – from the grower to the fuel supplier.

Åke Nordberg, JTI (the Swedish Institute of Agricultural and Environmental Engineering)

Biogas technology offers many opportunities and is a key component in bringing about a sustainable society. It is a technology that can be applied both on a small scale (at farm level) and on a larger scale (centralized plants), and the use of biogas is flexible. The technology can be applied both in the industrialized parts of the world and in developing countries, where it seems even more important from a sustainability point of view.

Biogas consists mainly of carbon dioxide and the combustible gas methane, and is formed when organic material such as manure, food residues and plants are broken down by micro-organisms in an oxygen-free (anaerobic) environment. The breakdown process, known as anaerobic digestion, takes place naturally for example in cows' rumens, on marshy ground and in waste dumps. In a biogas facility, this breakdown process takes place in controlled ways in a digester tank.

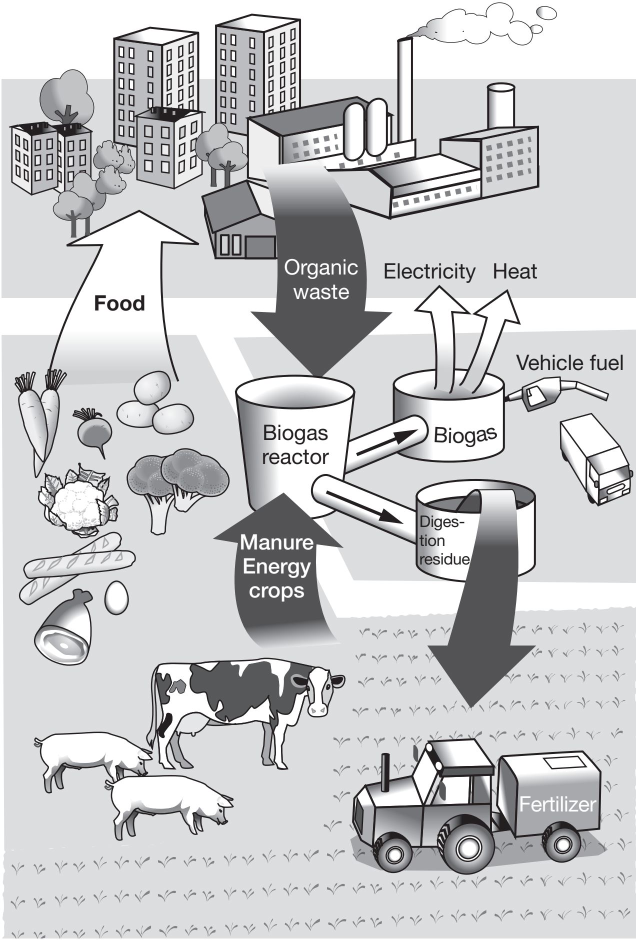
Biogas process with three functions

The biogas process is a multifunctional process, i.e. it fulfils many functions. Firstly, it functions as a sustainable waste treatment technology for organic waste from industry, households and agriculture. Secondly, it produces renewable energy in the form of biogas, which, without being purified, can be used in burners and engines to produce heat and electricity. If the gas is stripped of carbon dioxide and then compressed, it can also be used as fuel in vehicles or fed into the natural gas network. Thirdly, after the biogas has been extracted, the digested material can be used as fertilizer as it contains all the plant nutrients that were present in the original material.

The Swedish Parliament has decided that at least 35 percent of food waste from households, catering centres, restaurants and shops must be recovered via biological treatment by the year 2010. Biogas production contributes to fulfilment of the EU Biofuel Directive, which is intended to ensure that the equivalent of 5.75 percent of petrol and diesel sold must be biofuels by the year 2010. Building up expertise in the biogas arena is also very important in the development of technology and infrastructure for the future introduction of hydrogen as an energy carrier.

Old technology with new applications

The biogas process has historically been used since the second half of the nineteenth century, and China and India are home to many millions of small, simple family or farm systems in which the gas is used, for example, for cooking. In Sweden, biogas technology has been used in particular in sewage treatment works since the 1950s and 1960s to stabilize sludge. After the energy crises in the 1970s, however, interest grew in the production of renewable methane gas from



The biogas process does many things at the same time. It deals with organic waste, generates renewable energy in the form of biogas, and produces a digested residue that can be used as manure if it is sufficiently pure, i.e. does not contain excessive levels of environmentally disruptive material.

other organic material, including manure and industrial effluent. During the 1980s, many facilities were constructed to extract biogas from waste landfill sites, and since the mid-1990s a number of facilities have been constructed that process food waste and solid waste from the food industry.

The biogas currently generated in Sweden is produced mainly at sewage treatment works where the waste sludge is digested, and in waste landfill sites. In total, approximately 1.3 TWh biogas is produced each year. Of this, sludge digestion accounts for around 0.6 TWh, and the collection of landfill gas accounts for approximately 0.4 TWh. The remaining energy is produced at co-digestion plants or in industry. Co-digestion plants are located at fourteen places in Sweden, usually in connection with municipal waste management. In the majority of plants, abattoir waste and manure from agriculture are digested together with waste from catering centres, restaurants and households. There are only ten facilities on individual farms; many of them invest in ecological production.

Germany is one of the countries in Europe that produces most biogas. In 2006, there were approximately 3 500 biogas plants in Germany, most of them farm facilities. They are used to digest manure and waste from households and industry, but also energy crops such as maize. The country has long promoted biogas production, particularly for generating electricity. Most of the biogas also produced by smaller farm facilities is used specifically for electricity generation.

In Denmark there are 80 plants which co-digest manure with organic waste, of which 60 are farm facilities. During the 1980s and 1990s, requirements were introduced stipulating that farmers in Denmark needed to improve in exploiting manure from domestic animals. Building biogas plants therefore primarily became a way of meeting the requirements and reducing over-fertilization rather than a way of extracting bioenergy.

Raw materials for biogas

In principle, all organic material can be digested, but the technology is best suited to material that is easy to break down. Depending on the composition and moisture content of the organic material, the quantity of gas that can be extracted from the material varies. Abattoir waste (organs and cutting residues) contains a lot of fat and protein and is thus energy-rich. 270 cubic metres of biogas with a methane content of approximately 60 percent can be obtained from 1 tonne. Liquid manure contains a lot of water, and 1 tonne yields only 20 cubic metres of biogas with a methane content of approximately 60 percent. Source-sorted household waste yields approximately 170 cubic metre of biogas per tonne (63 percent methane), and grass and clover ensilage yields 150 cubic metres of biogas per tonne (55 percent methane).

In general, it can be said that it is good to mix different materials as this creates a stable process. To reduce the risks of the spread of pathogenic bacteria when the digestion residue is to be applied to arable land, the waste is hygienized before it is digested. This entails heating the material to 70 °C for at least one hour.

The scale of digestion of energy crops is to date relatively small in Sweden, but interest is considerable. In Västerås, a plant was built during 2006 which co-digests pasture plants and source-graded household waste. The cultivation of pasture crops for biogas production can yield many advantages for the farmer. Allowing pastures to be incorporated in the crop rotation system increases the humus content and improves the soil structure, which in the long term gives increased harvests. Incorporating pasture in the crop sequence cuts the risk of plant diseases and thus also the need for pesticides. Pasture also provides a first-crop value. This means that when the pasture is broken down, the harvest from the next crop may become greater. A cultivation area of 50 hectares is required to produce the equivalent of 1 gigawatt-hour (1 million kilowatt-hours) of biogas.

How biogas is produced

The biogas process is a biological process, and to ensure that this process functions as well as possible, the micro-organisms that break down organic matter into methane must thrive. They thrive best if the temperature is at a constant level and if the environment is pH-neutral and completely oxygen-free. The main factors that affect the process are temperature, water content, the composition of the digestion material, pH and the absence of any substances that inhibit the process.

The micro-organisms can produce biogas even at low temperatures, but become more active if it is warm, and the process then proceeds more quickly. The two commonest temperature ranges are 30–40 °C (mesophilic digestion) and 50–60 °C (thermophilic digestion). Thermophilic digestion proceeds nearly twice as quickly as mesophilic digestion. This means that the material does not need to be in the digestion chamber for as long and the size of the chamber can then also be reduced. Mesophilic digestion is, however, more stable. It is less susceptible to changes in temperature and less sensitive to materials that may disrupt the process. The mean length of time for which the material remains in the digestion chamber is 2–3 weeks.

Use of biogas

Heat production is the simplest and also commonest way of using biogas. The gas is burned in a gas boiler with a specially adapted burner. In general, efficiency is higher in gas-fired boilers than in oil-fired ones. This is due, among other things, to the fact that soot formation is less and that the flue gas temperature can be kept lower.

Production of both heat and electricity from the biogas usually takes place with diesel or Otto engines, which range from "passenger car size" to "ship size". The commonest solution is, however, for engines of "lorry size" to be used when electricity and heat are to be produced in biogas plants. These engines may, depending on size, yield 25–45 percent electricity and the rest becomes heat, most of which can be used for heating the process and, for example, buildings. There are also other ways of producing electricity and heat from biogas, namely via gas turbines, steam turbines or fuel cells.

In Sweden, electricity produced from biogas provides entitlement to electricity certificates. Anyone who produces electricity from biomass is awarded electricity certification which, when the electricity is sold to a supplier, allows for additional payment. This applies to farm facilities as well because payment is received per megawatt-hour of electricity produced. The price of biogas-produced electricity is, however, still relatively low in Sweden compared with in, for example, Germany.

Biogas as vehicle fuel

For biogas to be usable as vehicle fuel, the gas must be stripped of, among other things, carbon dioxide, hydrosulphuric acid, water vapour and particulates. The oldest and commonest purification technique is water scrubbers, which wash out the carbon dioxide with circulated water. After the treatment, the gas is dried. During the cleaning process, the methane content is also raised and thus also the energy value. The purified biogas contains 96–99 percent methane; originally, the methane content of the gas is approximately 60 percent. The effective calorific value for pure methane is 9.8 kWh per cubic metre, which is equivalent to the energy content of a litre of oil. After the purification process, the biogas has a quality equivalent to natural gas. Vehicles adapted to run on gas can thus be run on both biogas and natural gas (fossil gas). Biogas is a biofuel, while natural gas has a fossil origin.

Biogas to be used as vehicle fuel is compressed to a pressure of just over 200 bar before being distributed to users. Distribution can take place via gas grids or with special vehicles. Storage and refuelling of vehicles call for special technology. The fact that biogas is gaseous and under high pressure also means that special tanks are required on the vehicles.

Biogas is the only fuel that ended up in the highest environmental class according to the national Alternative Fuel Committee's report (SOU 1996:184) as emissions from the burning of biogas are very low. By international standards, Sweden is far ahead in terms of the use of biogas for running vehicles. According to the statistics for the first half of 2006, 10.2 million cubic metres of biogas for vehicles were sold. The equivalent figure for natural gas was 9.8 million cubic metres. This means that just over half of vehicle gas sold is biogas.

Methane is inherently a powerful greenhouse gas which is considered to be 21 times more powerful than carbon dioxide. The main sources of uncontrolled release are the keeping of animals, rice-growing and extraction of fossil fuels. Through controlled digestion of manure in which methane produced is combusted to form carbon dioxide, the greenhouse effect is reduced. It is important to minimize emissions of methane at all stages, from production, distribution and purification through to final use of the gas. The technological level of current biogas systems is high, so as to prevent methane emissions.

Biogas potential in Sweden

The quantity of readily convertible organic waste will not increase appreciably, thus restricting increased biogas production. The technical biogas potential in Sweden is put at between 10 and 20 TWh, 80 percent of which comes from agriculture. For an increase in biogas production to be feasible, raw materials from the agricultural sector must therefore be used, i.e. manure, harvest residues and in particular harvested energy crops.

To be able to tap the potential of farmyard manure, which totals at least 4 TWh, farm facilities must be expanded so that long-distance transportation of liquid manure can be avoided. The national report "Bioenergy from agriculture – a growing resource" (SOU 2007:36) proposes investment support of 30 percent of the investment costs to speed up the development of manure-based biogas production. The support is also proposed for co-digestion with other substrate up to 50 percent as this improves the methane yield. If such support were to be provided, this would mean considerably better economic conditions for investment in biogas technology.

Upgrading biogas to vehicle gas calls for relatively substantial investments. The profitability of such investment may be improved if a number of local biogas producers connect their facilities to a local or regional gas network and build joint upgrading facilities.

More effective collaboration

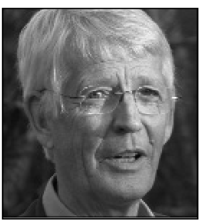
A combination of, among other things, the agricultural policy pursued, the objectives of increased use of bioenergy and the price of fossil fuels on the world market will drive the development of technology. This in turn improves the economic conditions for increased production and scope for selling the biogas. Agriculture thus acquires a more important role in society, partly as a supplier of raw materials for biogas production and partly as a producer of biogas in which the biogas is used for combined heat and power production or the production of vehicle fuels. In addition, agriculture is set to be of central importance in future work on tapping the plant nutrient content of waste.

For this to be possible, however, collaborative systems must be created between farmers, combined heat and power producers and fuel suppliers. The efficiency of the entire processing chain must be increased, from cultivation, transportation, treatment and recycling of plant nutrients to production of combined heat and power and fuel.

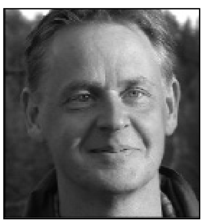
Åke Nordberg is a research and development manager at JTI (the Swedish Institute of Agricultural and Environmental Engineering). He has extensive experience of research and development in biogas technology; he has conducted laboratory and pilot studies and assessed production facilities.

Fertilization for more raw material from the forest!

In the long run, it is not possible to increase the extraction of bioenergy from the forest without affecting the supply of raw material to the forest industry. If the forest is fertilized according to demand, however, it is sufficient for both industry and the energy sector. With optimized fertilization, Norway spruce stands in Västerbotten produce as much as fertile stands in Scania. In addition, the nutrients do not leak into the groundwater. Researchers at the Swedish University of Agricultural Sciences have their own experience of this after twenty years of experiments. Despite this, this kind of forest fertilization is controversial and is not recommended by the Swedish Forest Agency.



Sune Linder, Institution for Southern Swedish Forest Science, Swedish University of Agricultural Sciences



Johan, Bergh, Institution for Southern Swedish Forest Science, Swedish University of Agricultural Sciences

Tomas Lundmark, Department of Forest Ecology and Management, Swedish University of Agricultural Sciences

Forests play an important role in replacing fossil fuels and reducing emissions of carbon dioxide, and the use of forest fuels has grown steadily over the last few decades. In 2005, biomass contributed 112 TWh to the Swedish energy system, with forest fuels accounting for approximately 80 percent. A continued increase in the use of bioenergy is of course desirable, but the question is how far we can get without adversely affecting the supply of raw materials to the forest industry – which is also our main producer of bioenergy.

Annual timber production in Sweden is currently just over 100 million cubic meters. In the long run, this cannot meet the raw material needs of both the traditional forestry industry and the growing bioenergy sector. In addition, more and more land users are making demands of forestry for anything from ecotourism to biodiversity. In other words, we need to produce more over a steadily shrinking area if all needs are to be met. Continuing to engage in forestry as we did in the 1990s is therefore insufficient. Forest impact assessments show that the potential felling levels throughout the first decade of the new millennium will hold relatively constant if forestry is carried on as now (Figure 1). This means that if "current" forestry is to be sustainable, the extraction of raw biomaterials cannot increase substantially other than by harvesting more from the trees felled, i.e. making the most of branches, tops, stumps, and small trunks.

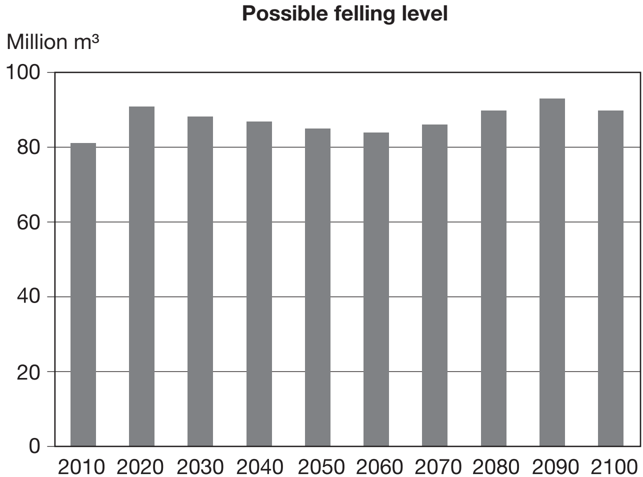


Figure 1. Forest impact assessments show that potential felling levels throughout the first decade of the new millennium will hold relatively constant if forestry is carried on as now. (Source: Swedish University of Agricultural Sciences)

What limits forest production?

What, then, limits the forest's production of renewal raw biomaterial? In this context, it is important to remember that the management of forests is governed by economic choices within frameworks set by what is politically allowed and biologically possible. Forests are managed in such a way as to optimize finances and not to maximize the harvest, and biological production capacity is far above the level exploited nowadays. Growth in Swedish forests has therefore not been "dictated by nature", but increased by around 50 percent during the 1900s thanks to forest owners' management and the approach of forest policy.

If we now want forests to stretch further, one solution to the problem is of course to allow this development to continue, i.e. by arranging for continued increased growth in the country's forests. To date, a large part of the increase in growth has arisen from felling volumes lagging growth, i.e. the timber stocks in forests have grown. This has meant that an ever greater stock of timber has arisen that yields ever more in terms of annual growth. We have now attained felling levels close to the annual growth rate, and timber stocks are therefore not increasing in the same way as before. How should we then ensure that growth continues to increase?

It is not the harsh climate or the fact that we have slow-growing tree species that primarily puts a ceiling on production in Swedish forests; rather, the commonest growth-limiting factor is the supply of nutrients – mainly nitrogen. To increase timber production, nitrogen fertilization of forest land was therefore started back in the 1960s. There were various reasons for this, but the attractive economic aspects of fertilizing forests and anxiety about a future shortage of raw materials were the dominant ones. The area fertilized increased quickly, and in the second half of the 1970s, more than 150 000 hectares per annum were being fertilized with nitrogen (Figure 2). The annual fertilized area was high until the end of the 1980s, but then decreased sharply, and in the last few years only just over 20 000 hectares have been fertilized, mainly within large forest holdings. Recently, however, interest in forest fertilization has started to grow again.

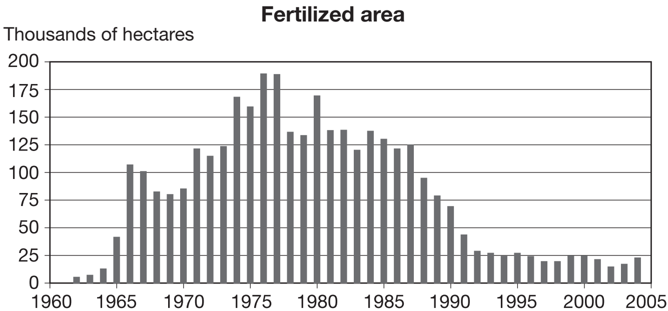


Figure 2. Annual fertilized area in Sweden over the period 1960–2004. Principally older stands were fertilized a number of years before final felling. (Source: the Swedish Forest Agency)

In practice, stands are, on moderately good land, fertilized towards the end of the rotation age. Fertilization gives a relatively immediate effect and after a normal one-time fertilizer application, the effect on growth is greatest three to five years later, before returning to normal levels after another few years. Normal doses of fertilizer are generally 150 kilograms of nitrogen per hectare, and such a dose is, on moderately good land, expected to lead to a total increase in growth of 15–20 cubic meters per hectare.

The main reason why fertilization decreased so sharply at the end of the 1980s was anxiety that lakes and watercourses would be acidified by leaking nitrogen fertilizer, leading to an adverse impact on aquatic organisms. Concern about further acidification of forests owing to air pollution and also stricter requirements from the Swedish Forest Agency concerning what land may be fertilized also played a part. Rules concerning what should be borne in mind when carrying out forest fertilization are set out mainly in the Swedish Forest Agency's general advice on the use of nitrogen fertilization of forest land.

It is worth noting that society's restrictive attitude to fertilization means that we give up the growth increase that the supply of nutrients provides and which is also a very profitable measure for forest owners. If the difference between the fertilization that we carried out in the 1980s and current levels is taken into account, it is evident that we give up around 2 million cubic meters of forest raw material each year. Converted to energy, this is equivalent to just over 4 TWh that could replace fossil fuels.

Biological production potential

The theoretical production ceiling on a forest stand is dictated by the amount of incident light during the vegetation period. Actual production is then the result of plant species, weather and access to water and plant nutrients. To be able to exploit the incident light, the latter must be absorbed by green leaves, whose photosynthesis drives the production system. The maximum leaf area in a forest stand varies according to tree species and stand age, but is usually directly dependent on access to water and plant nutrients. To optimize biomass production, it must therefore be attempted to obtain closed canopies as quickly as possible. This can be achieved by planting in closer formation and by improving access to nutrients.

To establish the biological production ceiling for Norway spruce, two experiments were established in the second half of the 1980s, one in Västerbotten (Flakaliden) in northern Sweden and the other in Småland (Asa) in southern Sweden. By ensuring that neither access to water (irrigation) nor access to nutrients (fertilization) limits tree growth, it can be established how the level of absorbed solar radiation in combination with the weather controls growth. A requirement in connection with the supply of nutrients is that it must be "according to demand" so that nutrient leakage is avoided.

Both in Flakaliden in northern Sweden and in Asa in southern Sweden, the growth of the stands increased drastically in response to the "fertilization according to demand" (Figure 3). In Asa, maximum production was not achieved with solid fertilizers as early-summer droughts affected the production results in some years. It is nevertheless interesting that the additional production with solid fertilizers in absolute terms (cubic meters per hectare) was the same at the nutrient-poor location in northern Sweden as at the fertile location in southern Sweden. In Asa, however, we obtained no additional production from nitrogen fertilization alone, but other nutrients must also be added.

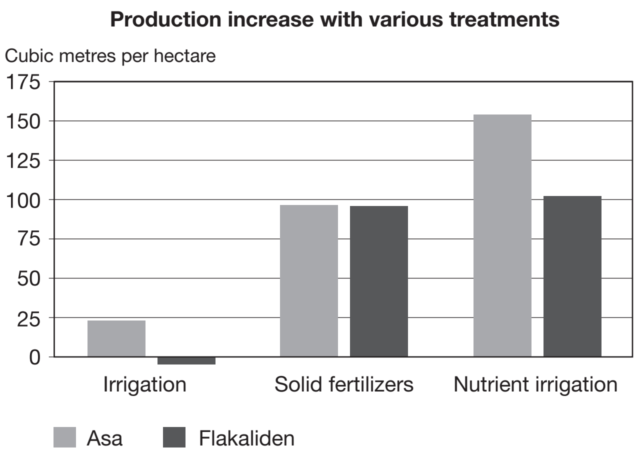


Figure 3. The increase in volume production as an effect of irrigation, annual supply of solid fertilizer and nutrient irrigation of young Norway spruce forests in Asa (Småland) and Flakaliden (Västerbotten) over the period 1988–2000. On the untreated control areas, production over the same period was 153 (Asa) and 43 (Flakaliden) cubic meters per hectare respectively.

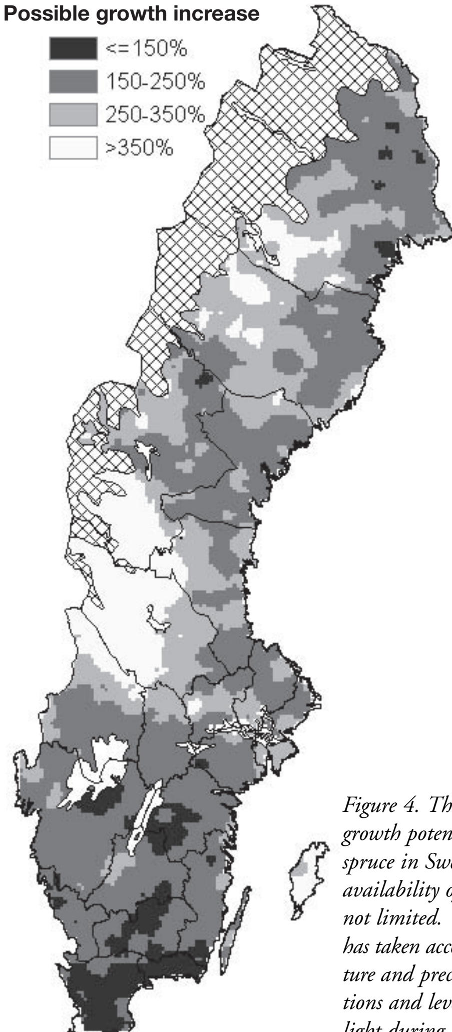


Figure 4. The map shows the growth potential for Norway spruce in Sweden if the availability of nutrients is not limited. The modeling has taken account of temperature and precipitation conditions and levels of incoming light during the vegetation period.

Practical production potential

In terms of practical application, it is advantageous from an economic perspective if fertilization can be performed, for example, every two or three years during the young forest phase instead of every year. Can the same growth effect be achieved if fertilization is carried out at intervals of one or more years? A new series of trials has been launched in which we study how much of the potential production is lost if the interval between fertilization operations is extended. The initial results after five years show that, in all stands, a substantial increase in production has been achieved and that fertilization every other year has yielded the same increase in growth as annual supply.

Based on the results from our trials with nutrient optimization, we have modeled where and by how much the production of Norway spruce could be increased in the present climate (Figure 4). The modeling indicates that a sharp increase in growth is possible in largely all parts of the country, and that in some regions it ought to be possible to boost production by more than 300 percent.

Nature chosen by Man

Many people are hesitant about further boosting growth in forests, not least some of our national authorities. Is "engaging in forestry" really sustainable any longer? Under international agreements, sustainable development must meet current needs without jeopardizing future generations' scope for meeting their needs. Sustainable development is therefore a matter of human life and human needs. As it is Man who, by his actions, affects nature, it is Man and

Fertilization according to demand in practice. The forest owner takes samples of the needles, which are then analyzed in a laboratory. The results are fed into a calculation program, which the forest owner can handle himself. The program calculates what the composition of the fertilizer should be to meet the needs of the trees. It is then just a question of mixing and fertilizing, and rejoicing that cracking growth is achieved without nutrients being leaked into the groundwater. (Illustration by Peter Roberntz) society that must choose what “nature” we are to have in future. In this way, Man bears responsibility for nature.

Forestry, environmental and conservation policy means decisions being taken by the State and society to take responsibility for the importance that society and people currently attach to nature. In this context, the research community has great responsibility for supplying the knowledge needed for all nature’s resources to be administered optimally for current and future generations.

In climate work, fertilization is an effective environmental measure which increases the growth of the forest and thus the supply of bioenergy. We could achieve the greatest effect north of Dalälven, where two thirds of the country’s forest is to be found and where there is a shortage of nutrients. For every percentage point of forest area in which nutrient optimization is allowed, additional production of at least one million cubic meters of stemwood could be achieved each year (2 TWh) plus 1 TWh of harvest residues. An advantage of fertilization is that the “delivery period” is short compared with alternatives such as replacing of trees species or genetically modified planting material.

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Johan Bergh is Associate Professor of Forest Management at the Swedish University of Agricultural Sciences. He conducts research on the impact of climate change on Nordic forest production and also works with practical applications of forest fertilization.

Tomas Lundmark is Professor of Silviculture at the Swedish University of Agricultural Sciences. He conducts research on alternative forest management practices which can meet the increasing demand for raw material from the forest.

Biotechnology yields more bioenergy from the forest

Improving forest trees by breeding is an effective way of increasing growth in the forest. By including biotechnology methods in the breeding program, it is possible to increase forest production considerably and more quickly, writes Sara von Arnold. The yield from highly improved and intensively cultivated forest should in the short term be able to increase by 50 percent. The larger the areas set aside for more intensive forestry with trees improved by breeding, the more bioenergy we can extract from the forest.

Sara von Arnold, Department of Plant Biology and Forest Genetics, the Swedish University of Agricultural Sciences

Photograph: Viktor Gärdebo

Around the world, forests are seen as one of the solutions to the problems of waning sources of oil, higher oil prices and ongoing climate change. Forests are a renewable source of both raw materials for industry and climate-neutral energy. The consumption of timber for industrial use around the world is expected to rise to 2.3 billion cubic metres by the year 2016, equivalent to an increase of nearly 50 percent since the year 1995. The increased need for forest products will necessitate significant felling. To avoid the clearance of large swathes of forest, forest growth must be boosted dramatically. Requirements for preserving natural forests and biodiversity are increasing at the same time.

In Sweden, forestry represents the greatest net export across all industries. Forests are being felled at a rapid rate; annual felling is running at 80–85 million cubic metres. Despite this, the stock of timber is growing because the annual growth rate is 105 million cubic metres. The forest policy committee (SOU 2006:81) proposes that the basis for forest policy be permanently enshrined, namely that the twin aims of production and the environment are equally important. However, the committee also proposes measures which entail timber production being increased by 25–50 percent over a time frame of 10–60 years. Among other things, the best possible plant material should be used for planting. Effective forest tree improvement by breeding combined with optimal growing conditions ought to be able to increase timber production by 50 percent.

Intensive and extensive forestry

Current forestry legislation stipulates that equal consideration should be given to both production and the environment on all woodland. It has been called into question whether this is the best solution for combining high and sustained production with no loss of biodiversity. Diversification of forestry at landscape level into more intensive and more extensive forms of forest management provides scope for maintaining high yields while at the same time allowing for the preservation of forest environments worthy of protection. With diversified land use, large areas will be set aside for extensive forestry and natural forests, while other, more limited areas are managed intensively. The primary aim of intensified forestry is to produce timber.

Besides the fact that existing woodland can be used for more intensive cultivation, Sweden has large areas of farmland taken out of service that can be used for forest production. Just as, in agriculture, agricultural crops improved by breeding have been intensively cultivated, we can now intensively cultivate improved and fast-growing forest trees.

Improvement based on genetic variation

Sweden's forests have been exploited in the service of people for as long as the country has been inhabited. In ancient times, felling usually concerned special timber, and people had high expectations about minimum dimensions. Such dimension-related felling left a growing mark on the forests as time passed, and the stock of trunks left behind were of poor quality. The genetic make-up of the stock of forest underwent negative selection. This has sometimes been called the forest's hereditary degeneration. In addition, seed for new plantations was often accumulated by collecting cones from the lowest and most branchy trees. The genetic make-up of our forests can be improved considerably by using plants that have been improved by breeding to rejuvenate the forests.

In the debate about the preservation of biodiversity and genetic diversity, improvement by breeding and preservation are often presented as diametrically opposed to each other. However, all improvement of forest trees by breeding is conditional on there being natural genetic variation in the species that can be used and administered. Preserving genetic variation is therefore a natural and necessary part of breeding improvement programmes designed to run for many generations.

Higher yields from improved seed

The development of a tree is determined by the interaction between its genes and the environment in which the tree grows. The genes may be affected by the improvement of forest trees by breeding, and the environment may be affected by forest management. A balanced combination of improvement of forest trees by breeding and forest management may therefore boost growth in the value of the forests in a sustained manner.

Improving forest trees by breeding is a very slow process in which economically significant characteristics are continuously improved. The improvement is obtained by plants being tested and selected on the basis of the characteristics determined for the breeding improvement programme. Each improvement cycle for pine and spruce takes 20–25 years. The selected trees are exploited for further improvement and may then be included in a new improvement cycle. The individuals with the best genetic make-ups (genotypes) are also used for mass propagation. This is done by branches from the best genotypes being grafted onto suitable main stems and being allowed to grow into new trees in a seed plantation. When the trees start flowering after 15–20 years, the seed is collected and used to rejuvenate the forests. Currently, most of the seed used in forestry is produced in seed plantations. Plants produced from existing seed plantations are expected to produce 10–20 percent higher yields than plants from unimproved seed. And plants from seed plantations laid out at the present time are expected to produce 20–25 percent higher yields.

A problem with traditional vegetative propagation is that once the best genotypes have been identified in the current breeding improvement programme, they have become too old to be propagated vegetatively with cuttings. Here, too, somatic embryogenesis can offer a solution. The embryogenic cultures can be stored in liquid nitrogen while the clones are tested in the field. Once the best clones have been identified after 15–20 years, the clone is preserved and can be propagated via somatic embryos. By using somatic embryos, the yield of trees can be improved and the genetic gain from the breeding improvement programmes can benefit forestry 25 years earlier. Swedish forestry companies are now testing how they can use somatic embryos to improve production.

Many people are afraid of cloning-based forestry and feel that this will bring genetic variation to an end. However, our coniferous trees are very dependent for their survival on various environmental factors, such as the interplay between daytime length and temperature. A specific clone can therefore be used only in a geographically limited area. Many different clones are therefore needed. In this respect, there is a great difference between forest trees and agricultural plants. The risks of a single clone being lost or of biodiversity being affected can be reduced sharply by selecting management measures and suitable clone mixtures. A number of independent analyses of the opportunities and risks of clone-based forestry have shown that the benefits outweigh the disadvantages.

Cloning: a tool for propagating plants improved by breeding

Biotechnology encompasses a large number of methods. In terms of the improvement of forest trees by breeding, methods that allow large-scale vegetative propagation (cloning) are of great interest. Another biotechnology method is the use of genetic markers to be able to identify valuable trees earlier and analyze how genes are expressed in them.

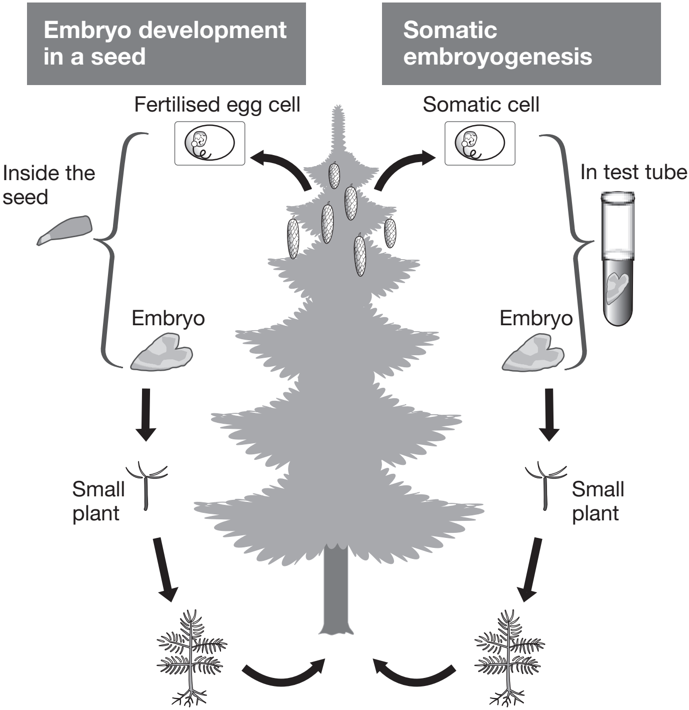
Every single tree (from sexual multiplication) has a unique genetic make-up (genotype) which has never existed before and which will never arise again. With vegetative propagation of a certain genotype, a number of genetically identical plants (clones) can be produced, plants which thus have exactly the same genetic traits. Through traditional vegetative propagation via cuttings, a limited number of genetically identical individuals can be produced.

However, a new method called somatic embryogenesis has made it possible to clone an (in principle) infinite number of plants from a specific individual (see Figure on the next page). When the seed embryo is isolated and cultivated on a medium with a well-balanced composition, the cells in the seed embryo are stimulated to divide. The number of cells increases rapidly. These cells can then be stimulated to develop into new embryos (somatic embryos), and all embryos have exactly the same genetic make-up as the original seed embryo.

Faster improvement by breeding with genetic markers

Traditionally, selection in breeding improvement work is based on the best genotypes being identified in field tests. A selection can be made only after the plants have attained a fifth of the rotation time, i.e. after 15–20 years for pine and spruce. This is a time-consuming and expensive way of working. An attractive alternative to field testing is merely to take small samples from seed or seedlings and investigate whether the individual carries the genes that regulate the characteristics for which improvement is sought.

One difficulty is that most characteristics for which improvement is sought are governed by a large number of genes. This applies, for example, to breeding improvement for growth and for resistance to pests, drought and cold. In recent years, it has become increasingly interesting to use different types of genetic markers in the genetic make-up to identify valuable characteristics. Forestry companies around the world



Propagation of spruce. Normally, embryos develop inside the seed after fertilization. When the seed grows, plants are formed, with each plant having a unique genetic make-up (on the left of the picture). In somatic embryogenesis (on the right), somatic cells (ordinary "body cells") in test tubes are stimulated to undergo a large number of divisions. The individual cells can then be stimulated to form somatic embryos. When these embryos develop into plants, all plants from the same original cell will be genetically identical to one another and to the individual from which the somatic cell was originally isolated.

are currently trying to develop strategies to exploit molecular markers to select for economically important characteristics at an early stage. This should make it possible to make the most of the genetic gain from the breeding improvement programme much more effectively and quickly.

Faster flowering increases the rate of breeding improvement

Intensive research is currently being conducted to shorten the time before trees flower. The idea is first to identify genes that regulate flowering. By then affecting how these genes are expressed, it becomes possible to stimulate trees to flower after just a few years, compared with 15–20 years, which is usual for pine and spruce. The aim is to shorten the breeding improvement cycles and thereby accelerate the breeding improvement work. Various methods are being developed which are intended to make it possible to activate the genes that stimulate flowering. Our agricultural crops have been produced after a large number of breeding improvement cycles. It has, for example, taken hundreds of cycles to obtain present-day maize by breeding improvement. In relation to our coniferous trees, Sweden is in the second improvement cycle. Everything that can be done to shorten the breeding improvement cycles and increase the genetic gain from each cycle will increase the growth and quality of the trees.

So far, this chapter has dealt with conventional improvement by breeding, and not with what is called gene technology, i.e. modifying the expression of various genes and obtaining genetically modified organisms (GMOs). In principle, the selected elite genotypes could be improved by modifying the expression for genes which regulate important characteristics. However, I do not believe that genetically modified conifers which grow for more than 50 years before felling and which are also wind-pollinated will be used in forestry within the next few decades. On the other hand, transgenic trees will play an important role as a tool in research to extend knowledge about how the characteristics of trees are controlled and passed on.

More bioenergy with trees improved by breeding

The improvement of forest trees by breeding is already generating trees with significantly higher yields than unimproved material. By including biotechnology methods in the breeding improvement work, it will be possible to produce high-grade improved conifers more quickly and effectively. The yield from high-grade improved and intensively cultivated forests ought in the short term to be capable of increasing by 50 percent. The greater the areas set aside for more intensive forestry with improved trees and the more effective the use of felling residues and roots, the more bioenergy we can obtain from the forest.

Improvement by breeding means that forest production can be increased markedly without threatening other environmental aims. We can obtain high growth without large doses of fertilizer, and thus reduce the risk of nitrogen leakage. Tree resistance to pests can be increased, thus reducing the need for chemicals.

Sara von Arnold is Professor of Forest Tree Cell Biology at the Swedish University of Agricultural Sciences in Uppsala since 1988. She leads a research group that studies developmental biology in conifers. Much of the work concerns embryo development, in which somatic embryos are used to study how development is regulated.

More fuel from the forest – with improved handling

Branches, tops, stumps and small trees – this is the range of products from the forest that can be utilized as fuel. In Sweden, only branches and tops have so far been utilized on a major scale. The hope is that extraction will increase. Handling in the supply system must, however, then become much more effective and the catchment areas must become greater.

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Magnus Thor, Skogforsk (Forestry Research Institute of Sweden)

When the Swedish Prime Minister's Commission to prevent oil dependence presented its report in summer 2006, more effective energy use and renewable fuels were strongly urged. The Commission's aims for Sweden entail, among other things, a halving of petrol and diesel in transport work and production of vehicle biofuels equivalent to 12–14 terawatt-hours (TWh) from forestry and agriculture, i.e. twenty times more than at the present time.

Since the 1970s, the forestry industry has assumed an increasingly important role in the national energy system. Tree fuels account for 100 TWh or nearly one fifth of Sweden's total energy supply. Tree fuels should be taken to mean forest fuel, by-products and lyes. Forest fuels contribute nearly one third of all tree fuel. Forest fuel is "non-industrial round timber" (for example, rotted logs), branches and tops (harvest residues) from final felling, firewood for private households and tall oil. The Swedish Forest Industries Federation have concluded in a report that the extraction of harvest residues can be doubled, an increase of approximately 8 TWh. New ranges, such as whole trees from clearing and thinning and stumps from final felling, can supply a further 11 TWh in total. Other commentators have arrived at even higher figures.

The supply of forest fuel must become more effective

Current forest fuel systems cannot manage with larger catchment areas and longer transport distances unless fuel prices are raised or handling is made more efficient so that costs are reduced. Currently, tree fuel chippings cost around 15 öre per kilowatt-hour. The equivalent oil price is at least 50 öre per kilowatt-hour. Fuel users on the margins thus have a high capacity to pay for forest fuel on condition that the plant allows such a replacement of fuel. A boiler that must be capable of being fired with forest chippings and other unrefined fuels is more expensive and makes greater operating demands than a facility that burns refined fuels, e.g. pellets or oil.

Significantly increased extraction of forest raw material for energy purposes means greater competition for the raw material. The challenge of doubling the extraction of forest fuel will probably be made more difficult by the lack of competent labour in a few years. For the forestry industry and the energy sector to be able to benefit from the possible volumes, the efficiency of the entire supply system for forest fuel must be substantially increased. This is in order to increase the size of the catchment area, to make extraction more effective where this is already done at the present time, and to be able to extract new ranges of product that have previously been left in the forest.

Current handling of harvest residues

During the lifecycle of a tree, forest fuel can theoretically be utilized in the form of harvest residues, stumps and small trees. In Finland, all these forest fuels are used commercially. In Sweden, it is only harvest residues that are exploited on a major scale.

The commonest harvest residue system entails the felling method being adapted so that branches and tops end up in piles besides the felling machine's tracks. The harvest residues are collected and transported with a converted forwarder, a forest tractor normally

Figure 1. Harvest residues are collected and transported with a modified forwarder, a forest tractor normally used for off-road transportation of timber.

used for off-road transportation of timber to highways (Figure 1). The forwarder places the harvest residues in a pile near the (forest) road. Usually, the pile of harvest residues is covered with cardboard to prevent remoisturization from rain and snow. On the highway, the harvest residues are usually split with a chipping cutter or crusher which either blows chips directly into containers or chip vehicles, or otherwise places the chips in a pile on the ground. These chips can then be picked up by a vehicle which is loaded by a separate loader, or self-loaded with the aid of a bucket-type crane. Transportation then takes place direct to the consumer or to a terminal.

Different ways of rationalizing harvest residue handling

The direct costs in the supply chain for harvest residues consist of more expensive felling as a result of adaptation, off-road transportation of harvest residues, comminution, forwarding in one or two stages, and storage costs and terminal handling. There are a number of ways that can rapidly increase efficiency.

The adaptation of felling can be improved. With properly performed adaptation, the yield per hectare and per object may increase by up to 50 percent. The harvester operator must make a few large and high piles of residues. During the collection stage, a store of harvest residues must be left, partly because it is not profitable to clean up the bottom layer and partly so as not to include gravel or soil. A few large piles mean fewer storage spaces, more full batches and thus more effective off-road transport. The piles must also be free from contaminants in the form of roots from undergrowth trees. In this way, the quality of the fuel is improved. Well designed harvest residue adaptation provides the basis for rational handling throughout the chain. It is for that matter not self-evident that the felling process is made more expensive by the harvest residue adaptation. Certain operators who are skilled in planning their work consider that performance instead improves.

Off-road transport can be developed. An articulated tractor for harvest residues can transport from four to more than ten tonnes per load depending on engine size and equipment. Training and information, together with good equipment, mean that the cost of off-road transport may fall. Again, it is relevant how the piles of residues lie from the start. The forwarder operator can also make things easier (or more difficult!) for the next part of the chain – the chipper – by his way of building up the pile. The location of the stack also affects the cost for the next part, which is usually splitting.

The efficiency of the comminution process can be increased. A chip cutter is a relatively expensive piece of equipment which should therefore be utilized as effectively as possible. Systems involving chipping direct from small piles of harvest residues in the cutting area should be avoided completely. Where comminution takes place (at depots, terminals or on the premises of consumers) is determined by a number of factors. It is important to review the entire operation at regular intervals so that one or two main systems are used and exploited effectively in relation to the structure at suppliers, contractors and customers.

Scope for integration with round timber handling and regeneration can be exploited. The chain of events from the time that a timber contract is signed until a cutting area is regenerated again entails many players and operations. A number of these could be co-ordinated and designed as "package solutions", which are profitable for forest owners and service providers alike.

Bundling technology was developed in Sweden in the 1990s. This entails harvest residues being compressed into round, log-like bundles directly in the cutting area. The idea behind bundling is to achieve less expensive transport on the ground and on roads, simplified and improved storage and less expensive comminution. Despite earlier major development efforts in Sweden, the bundling process has not yet achieved any actual application. There are many reasons for this, including the lack of suitable comminution facilities at terminals and delivery sites. Such facilities require large quantities and can therefore be considered chiefly during the new construction of major fuel-consuming installations. To date, the facilities constructed in recent years have, however, not made the most of this development potential. In Finland, the bundling technology was adopted when the major district heating power plant in Pietarsaari was constructed several years ago. 20–30 bundling machines are currently in operation there. The performance and cost profile is closely in line with analyses Skogforsk conducted several years ago.

Transport – a question of distance and load weight

The forwarding of forest fuel takes place in various ways, depending on the transport distance, volume and customer. The commonest method is to chip from piles of residues at the road side and then unload the chips into containers for forwarding. The system requires relatively large quantities of each object to justify the container handling. The container system is sensitive because all concerned are dependent on the entire chain functioning. To make the system less "hot", the chipper can unload the chips in a stack on the ground and the chips are then fetched from a self-loading chip vehicle fitted with a crane-mounted bucket.

Other systems may also be interesting under special conditions. Harvest residues are transported in unsplit form, with this being commonest over short transport distances where the customer has resources to comminute the material himself. This system is used by a few major heating plants with concentrated catchment areas and their own crushing gear.

If, on the other hand, the catchment objects and the recipients are small in size and many in number, a lorry fitted with a chip cutter ("cutter vehicle") with a trailer can be a good solution. Cutter vehicles comminute the harvest residues and spray them directly into the vehicle for transport and are thus completely independent of other players. By combining chip cutters and transport vehicles, a machine unit is lost, but the vehicle loses loading capacity as it must transport the cutter with it all the time. The cutter itself is also used less on a cutter vehicle compared with a specially built chip cutter. The system is less suitable over long transport distances.

Figure 2 shows a skeleton cost diagram for certain systems. The Figure shows that the transport distance is very important for the system's costs. In the case of very large piles of harvest residues and long transport distances, it can be worth having a large truck-mounted chip cutter which fills specially constructed chip vehicles. Round timber vehicles (lumber vehicles) fitted with sheeting both on the bottom and on the sides can be used to transport bundles of harvest residues. As the

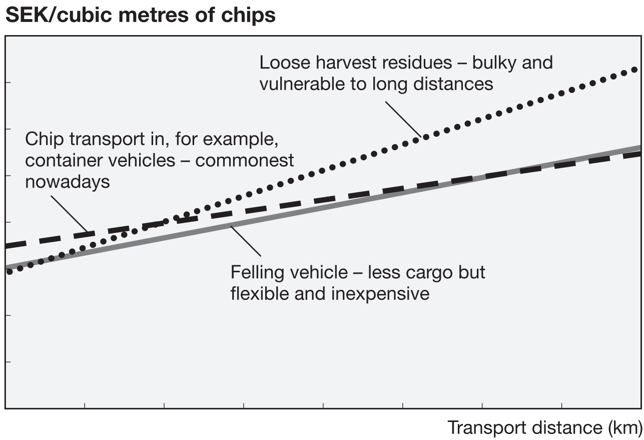


Figure 2. Skeleton diagram of the costs of different harvest residue systems as a function of different transport distances.

harvest residues are compressed in the bundles, full load weights are normally achieved. This also makes the system suitable over relatively long transport distances and above all if the bundles are comminuted in a large effective cutter. Substantially increased removal of forest fuel also results in increased transport distances. This means that one must consider other transport options, such as trains, boats and larger lorries than used currently.

New range – stumps and small trees

There is significant fuel potential in stump wood, and interest in exploiting stumps has grown in Sweden. Inspired by Finland, where stumps are already exploited

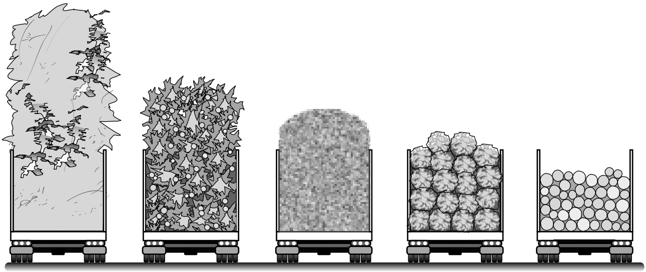


Figure 3. It is expensive to transport air. The diagram illustrates how bulky the same quantity of energy is in different forms from harvest residues to round timber. The energy content of 1 cubic metre of chips corresponds to 0.08 cubic metre of oil, i.e. 80 litres of oil.

for fuel purposes, stumps are now also being exploited on an experimental basis in Sweden. The technology is largely based on experience from the 1970s and 1980s, when the pulp industry made great efforts to exploit stump wood.

A typical system comprises stump lifting with an excavator fitted with a special unit which can often also be used to prepare ground for forest planting, if so required. Off-road transportation is carried out with forwarders which should have an adapted load space. The stumps are stored in piles in the cutting area or at the road side, where they are left for several months so as to be dried with the aid of sun, rain and wind and "washed" of earth, gravel and stone.

Comminution is carried out by a crusher. Forwarding can take place with similar vehicles as for harvest residue chips.

Despite washing, the stumps contain a relatively high level of pollutants in the form of gravel and stone. This makes great demands of the comminution equipment and the receiving boiler. A certain level of splitting should take place before forwarding as the stumps are bulky. There is still a great deal to develop and investigate before we can arrive at effective and sustained stump exploitation. Studies of technology and methods and also environmental impact are currently being conducted.

Small trees also offer interesting energy potential. Very little fuel is currently utilized in this context, chiefly due to low profitability and concern about business losses. If the entire cost of the operation affects the volume of fuel removed, the costs are often considered to be too high. Current development approaches include multiple tree-handling felling and processing units, exploitation of non-delimbed tree parts and various methods for direct splintering of the stock. Continued research and development in fuel supply from small forests is appropriate.

The entire system must be sharpened up

Technologies and methods are not yet adequate for making the potential volumes economically available and thus cope with an increased supply of forest fuel. All the components that form a market, namely technology, methods, organization and business, need to be rendered more effective and developed. Significant improvements in effectiveness from the business logistics perspective can be achieved by, for example, standardized routines, smoother links between the forest fuel organizations and parent companies and also better exploitation of existing purchasing, planning and timber handling systems. In addition, organizational structures and incentives for change in the operational parts must be reviewed.

If the activity is to be capable of being developed, all involved – fuel users, fuel suppliers, contractors and land owners – must be given an opportunity to earn money and boost their competitiveness. This can to some extent be achieved by the price increase that is now taking place. However, ability to improve the supply system will be crucial in determining how successfully the ambitious political aims set are achieved in the long run.

Anna Furness-Lindén is a master of Forestry and business engineering and researcher at Skogforsk within the Technology and More effective forest fuel systems programmes.

She conducts research on, among other things, how forest fuel systems and forestry business approaches can be developed.

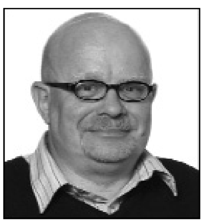
Berndt Nordén is a research engineer. He has considerable experience of practical studies of the entire supply system for forest fuel from stumps to boilers.

Magnus Thor is a Doctor of Forestry. He heads the Technology research programme at Skogforsk in Uppsala. The programme is designed, among other things, to achieve more effective technology and methods for felling, off-road transportation and forwarding of forest raw materials.

Is burning wood dangerous?

Many residential wood boilers in small homes in Sweden currently emit volumes of different substances that are dangerous to the environment and health. However, small-scale burning of biomass fuels need not be dangerous for humans and the environment. It is a question of having the right equipment, using it correctly and employing a good fuel, according to Bertil Forsberg, Lennart Gustavsson and Linda Johansson. Wood burning licenses and dust filters on chimneys may also be part of the solution to the health problems of wood burning.

Bertil Forsberg, Department of Occupational and Environmental Medicine, Umeå University



Lennart Gustavsson, Energy Technology, SP Technical Research Institute of Sweden

Linda Johansson, Energy Technology, SP Technical Research Institute of Sweden

The greenhouse effect has rapidly become one of the great political issues. Cutting the use of fossil fuels is a key task for the future. Until a century ago, we were largely using climate-neutral fuel in the form of wood to meet our basic needs. Log fires have, ever since our cave-dwelling times, been central to human life, providing heat and cooking facilities. The climate issue gives the burning of wood a fresh lease of life, albeit in technically more sophisticated forms.

Log fires in caves produced not only heat but also substantial air pollution. It is likely that particulates and unburned hydrocarbons affected human people's health and life expectancy just as now happens in poor regions where people live in simple huts and homes without chimney. When the log fire is enclosed in a stove, on the other hand, the flue gases are discharged from the home via the chimney and do not affect the internal environment. If the combustion process in the stove is poor, the ambient air may on the other hand be affected adversely. Climate neutrality is a major factor in favor of increased use of bioenergy in the future, but, from the total environmental perspective, the risk of other emissions must also be taken into consideration.

Emissions from small-scale burning of biomass fuel vary widely between different facilities and arise from technical design, and not least the user's knowledge and behavior. A lack of fireplace design can to some extent be offset by a skilled user who can spend time on looking after the burning process. However, in the normal situation in which the user has less experience and very little time for supervision, it is the design of the combustion equipment and the method of use that affect emissions most.

Time, temperature and turbulence

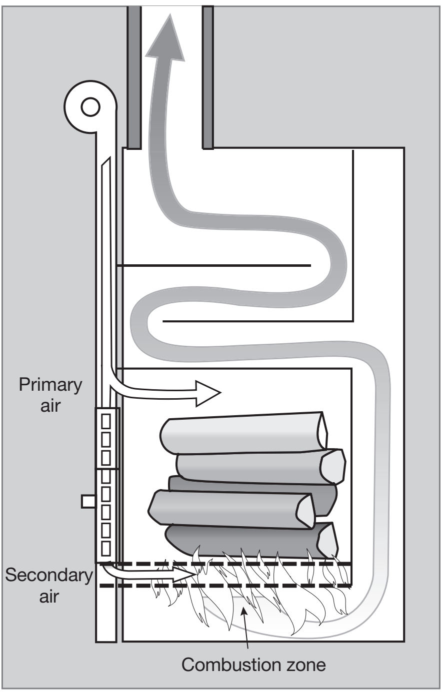
The conditions for good combustion with low emissions are usually described in terms of three Ts: Time, Temperature and Turbulence. This means that the combustion gases must have sufficient time (several seconds) at a high enough temperature (over approximately 1000 °C) and with adequate turbulence (mixing) to burn out completely before they cool down and the heat is utilized. This places great demands on how the fireplace is designed and how the combustion is controlled. It is, for example, more difficult to achieve effective combustion in a small fireplace fired with large pieces of fuel in the form of wood logs than in a large burner fired with wood chips. If, on the other hand, fuel with a smaller size is used, e.g. pellets, scope for control and for stable, effective combustion is improved.

A simple way of describing different combustion conditions is to assume a free log fire. It is largely impossible to get a single wood log to burn properly. All heat released radiates out to the surrounding area and the temperature becomes too low for the fire to be maintained. If, on the other hand, two or more pieces of wood logs are lit together, the heat is exchanged between them so that the gasification of the wood is maintained and the combustion process is stabilized. When the log fire is placed in a fireplace, even higher temperatures can be achieved by the space being insulated with, for example, fireproof ceramic. An old example of this is the tiled oven, which is made entirely of ceramic material. By supplying air in several stages (primary and secondary air) in a controlled fashion, good mixing with the combustion gases can also be achieved.

In older types of residential boilers, the fireplace is not insulated with ceramic material, but the walls are cooled directly by the boiler water, which is then heated and distributed around the home. The combustion temperature thus becomes too low for complete combustion, and the emissions are high. The emission levels are even higher if the combustion process is controlled so that the air supply is reduced when less heat is needed. By burning fewer logs, and thus more frequently, emissions can be reduced; for those away from home for most of the day, however, there is no alternative.

Down-draught combustion

Modern and environmentally approved wood boilers that meet the emission requirements laid down in the regulations of the National Board of Housing, Building and Planning usually have down-draught combustion. This means that only the lower layer of wood burns with the flames directed downwards in a ceramic fireplace which guarantees high combustion temperatures. The air is supplied in at least two stages with effective mixing of the secondary air in the combustion gases.



In down-draught combustion, air is supplied both from above and from below. The wood burns downwards via the bottom of the fireplace, and the air that enters at the bottom induces the gases to burn out completely.

To optimize the operation of this technology, the boiler must work on full power all the time. It is therefore connected to an accumulator tank in which the heat not currently released is stored as heated water for later use. This also makes the burning process much easier because a tank load can suffice for a full day and sometimes several days for most of the year. The accumulator tank is required for low emissions. For older water-cooled boilers, connection to accumulator tanks also provides scope for lower emissions by enabling throttle burning to be avoided.

Fireplaces located inside the home for direct heating of indoor air, e.g. stoves, stove inserts and tiled stoves, are often called local fireplaces. Usually, they have a ceramic lining of the combustion space, but large glass surfaces help lower the combustion temperature. The normally very small wood inserts and the fact that good supervision of the burning process is achieved affect emissions positively. However, scope for regulating the effect is often limited, and if the fire is throttled so that the room does not become too warm, the emissions increase.

Nowadays, many wood stoves are installed in newly built houses, often because it is cozy though also to ensure a warm home if the power is lost and to reduce the use of electricity. It is also possible, but not equally common, to choose a pellet stove and have the stove as an important part of the heating system. The use of pellets in pellet burners and pellet boilers for heating slightly older houses has, however, increased a great deal in recent years because many oil burners have been replaced. Wood pellets have a number of advantages over wood, chiefly because the user does not affect the combustion process in the same way as when feeding log fires. The fuel itself also has a lower moisture content and there is no danger of anyone burning moist fuel. This is always a risk in wood burning because fresh wood has a moisture content of 50–60 percent.

Thousands of substances in wood smoke

Residential wood- and pellet-fired equipment is, in Sweden, currently one of three major sources of fine particulates (PM 2.5, i.e. particulates less than 2.5 microns in size) in the outdoor air together with traffic and particulates from long-haul transport. Besides particulates, unburned gaseous substances are also emitted, e.g. benzene and nitrogen oxides. The smoke from the stove and wood boiler may actually contain thousands of substances, many of which exist in many other places and some of which have therefore been individually investigated from the health perspective. Gases such as carbon monoxide, benzene, butadiene and aldehydes have the same chemical structure regardless of their source. This means that substances that have been classified as carcinogenic for humans by the international body IARC, including butadiene, benzene and formaldehyde, are carcinogenic even if they originate in a beautiful log fire.

The polycyclic aromatic hydrocarbons (PAHs) present in wood smoke include some classified as carcinogenic. Some of these heavy hydrocarbons are not gases in ambient air but condensed onto soot particles. This means that soot particles can also be regarded as a cancer risk. Despite extensive evidence that wood smoke contains many carcinogenic components, no epidemiological studies have yet been conducted to elucidate how much the risk of lung cancer increases as a result of the kind of wood burning carried out in Sweden and the rest of the western world. The cancer studies available are based on more primitive conditions in which biomass from agriculture, such as sugar cane, is burned for heat or cooking purposes. Such studies have revealed an increase in the risks of cancer for those exposed, but cannot be used to quantify how great an effect our wood burning can have because different contaminants and concentrations are involved.

In addition to components harmful to health, the substances present in wood smoke also include methoxyphenols. These are antioxidants and counter the oxidation of other substances. Methoxyphenols are formed when the lignin present in wood is broken down. There have been headlines to the effect that wood smoke is useful because it contains methoxyphenols. However, there is no research to indicate that wood smoke is healthy, if anything the reverse is the case.

Heart disease commonest

For the individual, regardless of whether one has a stove indoors or is exposed to wood smoke via the air where one lives, the risk of contracting the very unusual disease of lung cancer as a result of the contaminants is very low. In terms of harmfulness, the particles of wood smoke are probably similar to other particles which have their origin in combustion. It is therefore the probability of suffering heart disease that increases most. The fact that the particulates level in the place where one lives affects the risk of early death, and in particular the number of deaths from cardiovascular disease, has, among other things, been demonstrated in several major American studies. If burning increases the particulates content of air where one lives by an average of 5 micrograms per cubic meter, mortality would, according to these studies, be expected to be increased by between 3 and 8 percent (chiefly as a result of deaths from heart and lung disease), which is a lot. This would also mean that the present-day low level of wood burning is responsible for several hundred deaths a year in Sweden. In the Biofuel–Health–Environment project, it was found that burning wood with old technology in the interior of northern Sweden can raise annual averages within urban districts by more than 5 micrograms per cubic meter.

The effects of wood smoke on mortality in poor countries, where people often light fires indoors without even a flue to discharge the smoke, are of a completely different magnitude. The World Health Organization (WHO) has estimated that 1.6 million deaths per annum and nearly 2.6 percent of the whole world's lost years of life are due to such indoor pollution.

Problems for people with asthma

If one's heating is managed poorly so that clear smells and soot affect the surroundings, it is nonetheless not the risk of cancer or heart attacks that the neighbors may end up criticizing. When the environmental inspector is contacted about problems with wood smoke, it is often asthmatics that are troubled by the irritant emissions. The soot particles and irritant aldehydes and phenols present in wood smoke aggravate asthmatics' airway problems. It can probably be said that the health effect of wood smoke that is most clearly demonstrated in epidemiological studies from the western world is an impact on symptoms, pulmonary function and the need for the care of asthmatics and other individuals with delicate airways. Many studies have shown how the complaint increases and how the number of treatment visits for breathing problems increases with rising particulate levels. The effects are evident on the very same day that the levels rise, and it does not seem to take very high levels for the risk to start increasing. The acute links have also been observed in Swedish studies. On the other hand, there is as yet little evidence that asthma as a disease arises from wood smoke or other contaminants, but the possibility of this cannot be discounted.

The question then arises as to what a log fire means in specific terms. It can certainly be acknowledged that a single poor user can cause at least short-term airway problems for his neighbors, particularly if they have asthma. A facility that produces low levels of emissions ought, on the other hand, to be unable to produce this effect. However, many small facilities together can affect air quality to a great extent, even if they generally function well. The World Health Organization has recently issued a new recommendation for fine particulates (PM 2.5), and considers that mean annual levels of more than 10 micrograms per cubic meter should not be accepted from the health point of view. If Sweden were to follow this recommendation and introduce an environmental quality standard with the same value, it will be very difficult from the health perspective to accept current emissions from small-scale burning, and it will of course not be possible to increase emissions. Most of the biofuel boilers that exist currently in small homes do not meet the emission requirements of the National Board of Housing, Building and Planning for the new installation of wood boilers, and most facilities lack accumulator tanks. There is therefore great potential for cutting emissions from the boilers.

Wood burning license on the wish list

There are examples of wood burning that is so poor that emissions result in releases of methane and an impact on climate, just like the burning of oil (although in the case of the burning of oil, it is the carbon dioxide that produces the impact on the climate). However, lumping together all kinds of biofuel burning as environmentally disruptive activities would be unfair because burning pellets and the very latest wood boilers produce low levels of emissions. It is also interesting that many of the older wood boilers are actually looked after well and also result in low levels of emissions. The emissions picture is further complicated by the fact that certain newer wood boilers (which meet emission requirements for new installation, according to the building rules of the National Board of Housing, Building and Planning) are mismanaged and give rise to high levels of emissions.

The conclusion to be drawn is that small-scale biofuel burning for climate reasons has a certain place in the energy system, but that both the equipment used and not least the user's skills and behavior determine the overall environmental impact. To ensure sustained residential biofuel burning in future, more research is needed on the health effects of wood smoke together with advances in burning technology. Another initiative that could cut emissions from poor burning habits would be the stipulation of wood burning licenses.

Another possibility is the installation of dust filters on chimneys. There are currently a number of prototypes that work, but no commercially available product.

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Salix cultivation yields added value – in addition to energy

Salix on arable land can add value to the landscape, increase biodiversity, treat sewage and remediate soil, and reduce carbon dioxide emissions, according to Pär Aronsson, Martin Weih and Inger Åhman. Currently, wood chips from Salix cultivation account for less than a tenth of one percent of Sweden's energy supply. However, such cultivation is expected to increase once the machinery improves and the price of bioenergy rises. Sweden currently exports plant material, cultivation technology and machinery to countries in greater need of biomass fuels than Sweden.

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It was not in fact bioenergy that was planned to be produced when, in the late 1960s, experiments were started with fast-growing deciduous trees in Sweden. Rather, the aim was to secure the supply of pulpwood to the forestry industry. The Swedish national forest survey had, after all, warned of a shortage of timber in the 1990s. It was realized very early that various species of *Salix* (willow) were the most promising in this context. After a few years, however, signs were emerging that the decline in timber would instead become a timber mountain. The year was 1973, crude oil cost 2 dollars a barrel – and the story could have ended there.

Why do we grow bushes on arable land?

With the first oil crisis in 1973, the pioneers of Salix research quickly switched their focus to bioenergy. 'Energy forest' was the term given to the new crop. At that time, growing energy forests on farmland was inconceivable. Instead, this had to be done on peat land and possibly farmland that had been taken out of service, which did not give the best conditions for growing. Nevertheless, the researchers persisted in conducting experiments on farmland and regarding the energy forest as any agricultural crop. With the changeover of agriculture in the 1980s, more highly productive farmland became available for energy forest cultivation, and an ambitious plant breeding program had been initiated by then. A start had also been made on learning to establish, manage and harvest the plantations in an improved fashion.

The term 'energy forest' was replaced by Salix. Generous plantation grants and set-aside subsidies brought about a rapid increase in the area to some 15 000 hectares in the first half of the 1990s. Agricultural policy then changed again when Sweden joined the EU, the price of wood chips fell and there was great uncertainty about the future. At the same time, growers and everyone else in the trade began to realize that the growth in Salix plantations was not as high as predicted. The older varieties used at that time were affected by frost damage and fungal attack, and the absence of fertilization in mature plantations made high rates of growth impossible on most land.

What have we learned about the crop and the cultivation system in the meantime and what do we know about the added value generated in Salix plantations? And what will happen in future?

How do we cultivate Salix nowadays?

Salix cultivation is nowadays completely mechanized. Special planting machines place cuttings (i.e. one-year pieces of stem, 15–20 cm long) in double rows in the spring. The double rows are adapted for the special harvesters used and which harvest a double row at a time and directly chip the wood. Harvesting takes place at intervals of 3–5 years during the winter, and the chips are usually transported directly to a district heating plant where it is burned as it is, i.e. without being dried.

After harvesting, new shoots emerge from the stumps, and the economic life of a Salix plantation is put at 20–25 years. In the best plantations, the growth rate is over 10 tonnes of dry matter per hectare per annum, but in a typical plantation planted with older varieties and which has not been fertilized, the growth rate is often less than 5 tonnes of dry matter per hectare per annum. Nowadays, Salix is cultivated on approximately 15 000 hectares of farmland in Sweden, and the chips harvested contribute 200–300 gigawatt-hours (GWh) to the Swedish energy system each year, which is less than a tenth of one percent.

Hybrid effects by plant breeding

Two plant improvement programs were launched in the late 1980s: a scientifically oriented program at the Swedish University of Agricultural Sciences and a commercially oriented one at the plant breeding company Svalöf AB. The starting material for the improvement process came from collections in Sweden, Russia and elsewhere in Europe.

The *Salix* family shows considerable variation in terms of growth habits, ranging from small creeping bushes to high trees such as Crack willow. It has emerged that the bush-shaped forms are best suited to coppicing. Osier (*Salix viminalis*) and Velvet willow (*Salix dasyclados*) are the two species that form the basis of the breeding material. The Salix family is unusual in that it is often easy to make hybrids (crosses) between species.

In certain combinations, hybrid effects are then achieved in which the progeny grows better than both parents. Such an example is the Tora variety, which is a cross between European Osier (*S. viminalis*) and Siberian Osier (*S. schwerinii*). Tora yields on average 60 percent more than the variety that was common in plantations when improvement by breeding started. In addition, it is not susceptible to the most serious pathogen in the plantations, namely leaf rust. Frost tolerance can be improved by crosses with Russian plant material but not all material from Russia exhibits frost tolerance. To test for this, promising material is cultivated in a "frost hole" in the Sala area of Svealand; there, night frosts are common even in the growing season. As a result of such tests, frost-tolerant varieties are now available on the market.

Salix research on exports

Another characteristic that has been improved by breeding is growth habit. To make harvesting easier, the stems must grow upright, and not bend at the base. To make the handling of cuttings easier, too, the one-year shoots should be straight and not branched. Small twigs on inwintered one-year-old shoots are usually due to the tip having been damaged by an insect or a grazing mammal. Selections against tip damage have meant that most of the new varieties suffer less such insect damage generally than the old varieties.

All in all, improvement by breeding has made considerable progress in a short while, largely thanks to the wide variation in plant characteristics that existed in the starting material, though also because not only increased growth but also increased resistance to pests and diseases has been prioritized at the selection stage. Improvement by breeding has also been facilitated by the fact that the bushes are either male or female, which makes crossing easy.

Breeding is now focused not only on use within the Nordic region but also on varieties for cultivation in Great Britain and continental Europe. In many of these countries, the lack of biomass fuel is much greater than in Sweden. As a result of the far-sighted investment in Salix, Sweden can now export plant, cultivation technology and machinery. It may actually be the case that Swedish Salix research will have a greater impact in countries other than Sweden!

More biodiversity

Salix plantations often have a poor reputation among environmental organizations, partly because they are considered to threaten biodiversity. Problems associated with Salix plantations are, however, often due to unsuitable location, design (including variety selection) and management of the stock. For example, biodiversity may decrease if large plantations are established in previously forested land, but this scarcely happens in Sweden. If, on the other hand, Salix plantations replace fields of cereal crops, biodiversity may *increase*, particularly if the plantations are small.

Proximity to native deciduous forest is also very important; a native wood nearby the Salix plantation will facilitate the migration of birds, insects and plants and, thus, increase biodiversity. Deciduous forest can also act as a retreat area where animals can survive when the Salix plantations are harvested every three or four years. Salix plantations should obviously be avoided in or close to natural environments of high conservation value such as residual arable land, meadows and pastures in an increasingly closed forest landscape.

Salix plantations may therefore frequently result in increased biodiversity from a landscape perspective. Through a number of measures concerning location, design and management of the plantations, the value of Salix plantations for biodiversity can be further *increased*, e.g.:

- locate plantations close to existing native woodlands and/or incorporate 'islands' of native trees within large plantations
- harvest parts of plantations in different years
- plant different species or varieties (preferably of different sex) in the same plantation; different varieties may be planted in sections or parallel strips in order to facilitate harvest actions
- apply chemical weed control only during plantation establishment
- do not apply more nutrient fertilizer than the trees demand during a growing season

- leave buffer zones without any crop or with native vegetation on the edges of plantations

Some of the suggested measures nevertheless may reduce the economic profit for the grower. Most Salix plantations are motivated, established and managed on a purely economic basis, and location, design and management must be planned accordingly. Being able to balance things cleverly in the light of these conflicting aims is a major challenge!

Higher landscape value in southern Sweden

A Salix plantation has a major impact on the landscape, and the fear is sometimes that such plantations may block views in traditional open agricultural landscape. This risk can be avoided if the planning of Salix plantations is preceded by a landscape analysis. Generally, the landscape impact of a Salix plantation largely depends upon the appearance of the existing landscape. Whether or not the landscape is adversely affected depends also upon subjective perceptions of Salix plantations generally. If it is assumed that Salix plantations are alien and ugly elements of the traditional cultivation landscape, the conclusion will be that the plantations should be "hidden" so that they do not alter the appearance of the landscape.

Instead, one can focus on the potential that Salix plantations can actually offer in terms of enhancing the value of the landscape. For example, the landscape impact of Salix plantations in southern Sweden has been investigated, and the conclusion was that the plantations can enhance the aesthetic value of the landscape by adding variation and structure to the often monotonous agricultural landscape of southern Sweden. However, if the plantations become too large, the landscape may be adversely affected. The visual impression created by large blocks of Salix plantations may however be improved by the introduction of a marginal zone of native bushes and trees. The conclusion is therefore that Salix plantations may not only improve biodiversity, but also increase the aesthetic value of the landscape by adding variation and structure in certain agricultural landscapes.

Salix is good for the climate

A Salix plantation takes up and binds a great deal of carbon dioxide when it grows, but as much carbon dioxide is released when the harvested chips are burned. Some carbon dioxide is nevertheless bound up in stumps and thick roots, and possibly also in the ground in the form of slowly degrading leaves and fine roots.

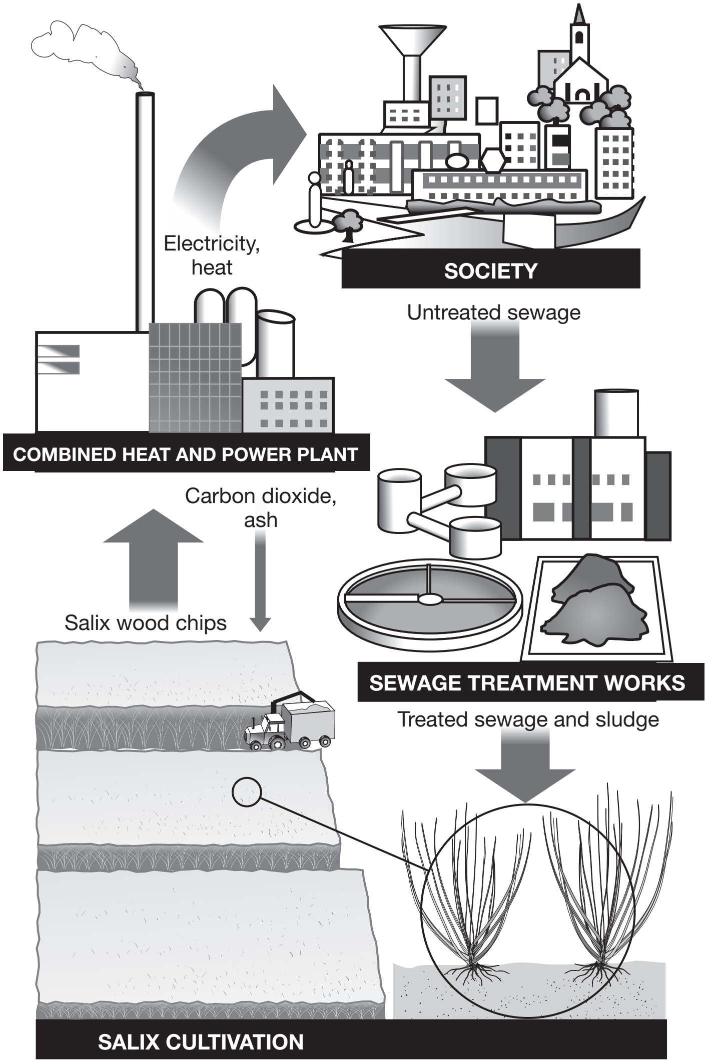
The major positive effect of Salix plantations lies mainly in the fact that Salix chips replace fossil fuels such as coal, oil and natural gas, which all make net contributions of carbon dioxide to the atmosphere. The higher the growth rate in the plantations, the more fossil fuel can be replaced. Large and intensively managed Salix plantations are consequently good for the climate.

Salix for remediating water and soil

Salix plantations have proven to be surprisingly effective in taking up plant nutrients. Compared with other agricultural crops, nitrogen leaching from Salix is very low. Greater areas of Salix could therefore reduce the eutrophication of the sea.

Since the 1980s, Salix plantations have been established in ten locations in Sweden for treating sewage, or in some cases for evaporating water. Interest in such systems grew appreciable in the 1990s, when many Swedish sewage works were compelled to increase the level of nitrogen purification. In a number of places, it was then chosen to hire farmers to grow Salix in the vicinity of the sewage works (Figure 1). The local authority built irrigation systems and in some cases dams to be able to store sewage during the winter season. The investment costs for such systems were substantially lower than for conventional nitrogen treatment, but it has not yet been clarified what the running costs and service life of the system are like.

Figure 1. The picture shows a multifunctional system in which Salix is used for treating domestic wastewater before then being used in a combined heat and power plant. The community's sewage is stripped of nitrogen, among other things, in the Salix plantation.


Electricity,
heat
SOCIETY
Untreated sewage
COMBINED HEAT AND POWER PLANT
Carbon dioxide,
ash
SEWAGE TREATMENT WORKS
Salix wood chips
Treated sewage and sludge
SALIX CULTIVATION

It has emerged that nitrogen is purified very effectively in sewage-irrigated Salix plantations, partly through plant uptake and partly through microbial conversion of nitrogen to nitrogen gas, so-called denitrification. The farmer earns money as a recycling entrepreneur, though also as a result of the Salix plantation growing very well when it is both irrigated and fertilized. There are also disadvantages with the system. It requires large tracts of arable land in the vicinity of the communities' sewage works, groundwater supplies must be protected from bacteria and other micro-organisms in the sewage, and all denitrification entails some release of dinitrogen oxide, which is a very powerful greenhouse gas. These aspects must be addressed when treatment systems are planned.

Reduces cadmium levels in the soil

Large quantities of cadmium were introduced into Swedish agricultural land in the twentieth century. This happened chiefly via phosphorus fertilizers and air pollution, though also via the application of sewage sludge from sewage works in the 1970s and 1980s. This cadmium input in turn led to elevated cadmium levels in the food, and the contribution via the food is big enough to cause health problems in the form of impaired renal function and skeletal decalcification.

What does this have to do with Salix? The fact is that most varieties of Salix take up significant quantities of cadmium from the soil, and in theory a field's cadmium levels could be restored to the natural concentration by growing Salix for 25 years (Figure 2). Most of the cadmium by far then ends up in the flue gases in the heating plant and gets caught in the stack filter together with the fly ash. A large proportion of Salix chips in the fuel mix can therefore be assumed to lead to elevated cadmium levels in the ash, which makes it difficult to return the ash to the agricultural land. Technology is available for stripping ash of cadmium and other heavy metals, but as no-one is willing to pay for the environmental benefit that this would entail, we have to live with a "hobbled" ecocycle and food containing cadmium.

Salix cultivation is expected to increase

Continued plant improvement by breeding, partly with the aid of the latest breeding technology, will lead to new varieties that grow more quickly and are more resistant to pests and diseases. Some will be adapted for dry and warm areas in southern Europe, while others will be specially adapted for wet, dry or particularly fertile land in northern Europe. Most stocks of Salix will in the future probably also be cultivated for energy purposes. However, a mosaic of plantations for different purposes is also conceivable, e.g. plantations for treating soil or landscape care, where both the landscape and environment are to be enhanced.

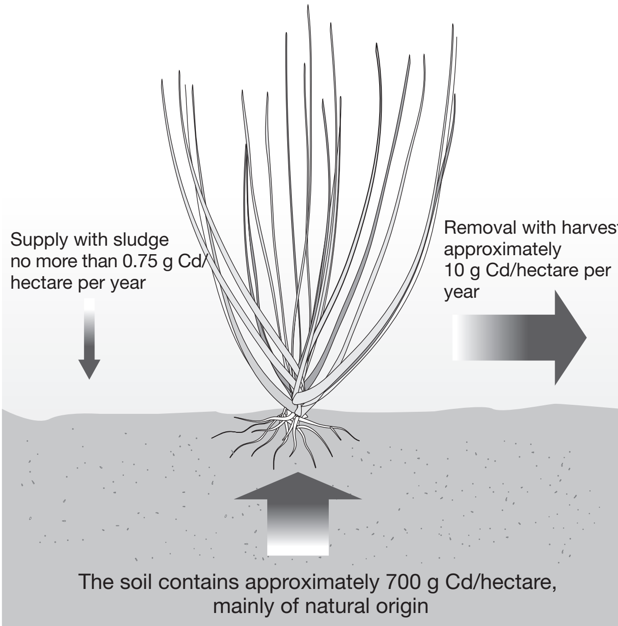


Figure 2. Salix takes up significantly more cadmium (Cd) than is supplied with wastewater and sludge, and thus cleans the soil in the long term. Cadmium is easy to handle in Salix plantations; such handling is much harder with the other heavy metals.

The continued development of planting and harvesting machinery will gradually lower costs for the grower, while a steadily rising bioenergy price will increase income. Increased growing of Salix in Sweden can therefore be expected. New players and new business models may emerge on the market, which may also help improve profitability for the grower.

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Martin Weih is an Associate Professor of Plant Ecology at the Swedish University of Agricultural Sciences. His research chiefly concerns the resource economics of all plants in connection with biomass production in Salix plantations.

Inger Åhman is an Associate Professor of Entomology and is employed at the Swedish University of Agricultural Sciences. She has worked for many years on the improvement of Salix by breeding, particularly in terms of resistance to various pests.

Energy crops on arable land – who will grow them?

Energy forest, reed canary grass and hemp – or grassland, cereals and oil plants? What is it that induces a farmer to choose crops? What is economically worthwhile? And what is the situation in terms of employment? It is hard for new crops at the start. A paradox is that the greater the demand for bioenergy, the more profitable it becomes to grow the traditional crops, writes Håkan Rosenqvist.

Håkan Rosenqvist, Department of Plant Production Ecology at the Swedish University of Agricultural Sciences and the Department of Environment and Energy Systems at Lund University

The bulk of the area of Sweden covered by energy forest was planted over the period 1991–1996. Interest in perennial energy crops increased in the early 1990s. This interest was sparked by, among other things, expectations in Sweden about the reduced profitability of food production, support for taking areas of arable land out of food production and start-up support for the planting of, for example, energy forests. Taxes on fossil fuels were also raised, making bioenergy more competitive.

After 1996, relatively small areas were planted with energy forest. In 1995, Sweden joined the EU, and the profitability of cereal growing improved. This reduced the incentive to grow energy forest. Start-up support for energy forests was reduced in 1997 to a lower level than before. For the first six years of the new millennium, the profitability of cereal growing declined; despite this, relatively small areas were still being planted with energy forests.

Straw fuels such as the grasses reed canary grass and hemp are also grown on very modest areas in Sweden. This is due partly to the current problems with selling these products. In relation to energy forest, there are sales outlets for the chips, but the small area involved has meant that there are few players involved in planting and harvesting, and this has led to weak competition. The small area involved and thus the weak competition have contributed to relatively substantial price differences between what the heating plants pay for energy forest chips and what the grower receives for his harvest. This explains in part why the scale of energy forest cultivation has not grown further.

What should the farmer grow?

There are many aspects to the question of what is suitable for the individual farmer to grow. Besides biological aspects, the farmer should consider what fits in with his enterprise and the operator's aims, what resources are available, what the changeover to a new crop entails, what a new crop means in terms of the farmer's employment, how the selection of crops affects liquidity, what the perceived risks are like, the potential for sales, and profitability.

It is the individual operator who determines most aspects in his enterprise, even if regulations laid down by authorities and financial aspects set limits. Areas of production that fit in less well with the operator's aims should be subject to more stringent requirements in terms of yields than those that coincide with the aims. If a farmer wants employment in his enterprise and wants to grow cereals, energy forests and reed canary grass often do not fit in with the aims, and this leads to requirements for a greater financial net return per hectare with reed canary grass and energy forests than with cereals.

If there are resources for cereal growing, such as grain threshers and machinery for tillage, a change in the form of reduced cereal growing means that, in the short term, expenditure is required. There is also generally greater knowledge of existing areas of production than new ones, such as energy forests, and this can impede new production.

Energy forests: a major change

In many cases, it can be easier to accept a smaller change than major changes. Continuing with what one does entails the least change. This means that cereals and rape for energy purposes are very easy for the grower to accept. Hemp must be established and harvested every year, which represents a moderate change for the grower. Reed canary grass represents a major change for cereal farms in that it is a perennial plant and harvesting takes place largely with machinery not used in cereal growing. Energy forests constitute the energy crop entailing the greatest change since it is a perennial plant, is harvested every three to four years, is woody, alters the skyline, makes little use of the farm's existing machinery following establishment, and leads to low levels of employment for the farmer.

Perennial energy crops usually lead to reduced employment for the farmer. If time is freed up, there may be scope for other employment, which in turn affects income and liquidity. Time freed up can also be used for increased leisure. Liquidity is affected by the choice of crop, partly because the machinery needs differ and partly because different amounts of money are tied up in the crop in the field. Neither reed canary grass nor energy forests require the farmer to have a great deal of machinery of his own. Most haulage for these two crops is hired in. The start-up cost for hemp is similar to that for cereals, and that for reed canary grass is similar to that for pasture, while energy forests have higher start-up costs. On the other hand, start-up support is available for energy forests. In 2007, the support was SEK 5 000 per hectare in Sweden, covering half the cost of start-up.

Energy forests result in a greater perceived risk

Most operators prefer less risky alternatives to more risky ones if the economic return is the same. The risks seem different for different crops, and the risk influences operators' requirements in terms of returns. It is the perceived risk that operators act on, as it is difficult to say how great the actual risk is. Energy forests are often perceived as being more risky than for example cereal growing, as farmers do not know as much about it. This means that the requirement for economic returns becomes higher for energy forests.

However, it is not sufficient to examine the risk of the energy crop in relation to, for example, the risk of cereal growing. The operator's entire portfolio of activities needs to be studied. Even if an individual area of production has a high perceived risk, the operator's total risk may fall if the co-variation is low or negative between different economic activities. The impact of the weather on the size and quality of the yield ranges sharply between, for example, energy forests and cereal growing. This may reduce the enterprise's total risk if the ratio of area between energy forests and cereals is just right. There are also differences in market risks between energy crops and food.

Easier to sell energy forest chips than straw fuel

In Sweden, there are many heating plants and district heating power plants that burn wood chips. The bulk of the chips comes from forestry. Energy forest chips will in the foreseeable future account for only a small proportion of fuel supply in Sweden compared with forest chips. It is an advantage that energy forests are harvested during the cold part of the winter and that harvesting coincides with the time of the year when the need for heat is greatest.

In Sweden, there are only a relatively small number of heating plants that are adapted to burn straw fuels, and this creates selling problems. Straw fuels that are pressed into bales are often also more expensive to handle in large heating plants than chips.

Energy forests have the lowest production costs

For burning in large plants, energy crops can, in terms of costs, be classified into three main groups:

- Energy forests (e.g. Salix), which is the least expensive per megawatt-hour
- Perennial straw crops (e.g. reed canary grass)
- Annual straw crops (e.g. hemp), which is the most expensive per megawatt-hour

Although energy forests such as Salix have high start-up costs, it takes many years before the crop needs to be planted again. If the start-up cost is apportioned over the life of the plantation, it is considerably lower than for annual crops. The energy forest is normally chipped in connection with harvesting and does not usually have to be stored for a longer period. The chips are usually less expensive to handle than straw fuels pressed into bales. Of the various crops in Table 1, it is apparent that energy forests represent the least expensive energy crop to grow and handle up to the customer stage.

Perennial straw crops such as reed canary grass have low start-up costs and long lives. This means that the start-up cost is very low compared with energy production. A general drawback of straw crops is that they are often expensive to handle and store. Reed canary grass for energy purposes is generally harvested in the spring, when the energy demand for heat is relatively low. Usually, reed canary grass needs to be stored before use. Annual straw crops such as hemp have high start-up costs as the plantation must be established each year. In addition, it is a straw fuel which in many cases entails high handling costs.

Table 1. Assessed production cost in SEK per megawatt-hour for various crops and assumed yield levels for a Swedish region (Götaland's northern plains). The costs include interest, all machinery costs, overheads, storage costs for straw fuels and 30 km of transport. Contributions and land costs are not included.

Production area	Salix	Hemp	Reed canary grass	Wholegrain (straw+grain in bales)	Autumn wheat	Oats	Autumn rape
Yield (tonnes of dry matter per hectare per year)	8.2	6.2	5.0	6.7	4.8	3.6	2.6
Production cost (SEK per MWh)	140	325	228	268	319	354	425

The production costs in Table 1 can be compared with prices for wood fuels free at heating plants in Sweden, which were approximately SEK 150 per megawatt-hour in the winter of 2006/2007. It can be seen from the table that the crops that lead to the greatest change for cereal farmers, namely energy forests and reed canary grass, have the lowest production cost. However, large users' willingness to pay is considered to be higher for wood chips than for baled straw fuels. This makes straw crops such as reed canary grass, hemp and wholegrain cereals less interesting in terms of profitability than appears from the table, which merely shows the production cost before further processing or burning.

Besides energy production, farmers may have other reasons for growing energy crops, such as hunting. Energy forests provide protection for wild animals, which improves prospects for, among other things, roe deer and pheasants.

Fertilization with sludge and sewage

The application of sludge and sewage to energy crops takes care of plant nutrition in a manner that makes economical use of resources. For the grower of energy crops, the costs of purchasing commercial fertilizer are reduced, and there is scope for securing greater yields. However, the greatest gain is in cost savings for the sewage works. The costs of eliminating nitrogen and phosphorus are substantially higher per kilogram of nutrients in sewage works than what it costs farmers to buy in nitrogen and phosphorus as commercial fertilizer.

The use of sludge and sewage can lead to increased bioenergy production in two ways. Firstly, it leads to a larger area of energy crops when profitability increases. Secondly, the yield is greater per hectare of energy crop irrigated with sewage or fertilized with sludge. The proportion of current energy forest plantations that have been fertilized at some time with sludge is relatively high, while fertilization via sewage irrigation is relatively uncommon.

Tough at the start for new crops

Agriculture is currently engaged mainly in the cultivation of grassland, cereals and oil plants. Production equipment, knowledge and traditions exist for these crops. There is also infrastructure with cereal receiving facilities, etc. that are adapted to the traditional crops. This makes it harder to introduce new crops on a large scale over a short period. Energy forests are the crop with the lowest production cost per megawatt-hour in large parts of Sweden. This is despite the fact that it is grown on relatively small areas. Salix is currently grown on approximately 13 000 hectares, accounting for roughly 0.5 percent of the area of Sweden covered by arable land. There are a number of conceivable reasons for this. There is no tradition of growing the crop, and both growers and advisers have little knowledge of it. The crop means a radical change for the farmer, existing machinery cannot be used, and energy forestry provides little employment. The fact that the existing area of energy forest in Sweden is small means that there are few players and that costs are high.

When deciding on growing new perennial crops such as reed canary grass and energy forest, a farmer needs to take a view on expected income from existing production as well as alternative production. If the farmer has machinery for cereal growing, this means that this machinery is utilised less well if the cereal growing is reduced. As a result, the farmer may, in spite of everything, carry on growing cereals even if this is not the most profitable alternative in the long term. The transition to energy crop production is eased by the use of agricultural machinery pools and also by other machinery collaboration on both energy crops and conventional crops.

The fact that crops are grown on a small area means disadvantages in terms of economies of scale and high costs as long as the area remains small. This means that energy crops which, in the long term, could become more profitable than traditional agricultural crops will in all likelihood not start to be grown on a large scale in the coming years unless radical steps are taken to improve the conditions. This is a problem facing the introduction of crops that do not require the same deployment of resources as traditional agricultural production in the form of pasture, cereals and oil plants.

Cost reductions that can be achieved by growing crops over a large area stem from, among other things, better organisation, better logistics, increased competition, greater knowledge, better and more effective machinery as a result of development work, mass production of machinery, better annual use of machinery, shorter distances between different fields and increased field size, and increased plant improvement by breeding with greater yields and more reliably growing varieties.

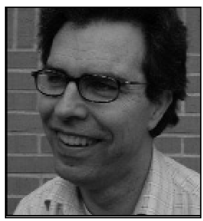
Paradox

If global bioenergy use increases, this will have the effect of raising prices of, among other things, cereals and oil plants as demand grows for products produced on arable land. This applies both to cereals and oil plants regardless of whether they are used for food or energy. Profitability for farmers in growing these traditional crops will thus increase in the case of increased demand for bioenergy. Many farmers will thus have less of an incentive to take on energy crops such as energy forests, even if the production cost per megawatt-hour is lower for energy forests than for cereals and oil plants. As a number of special machines are used for growing energy forests, the area must be sufficiently large for the production cost to be low enough per megawatt-hour.

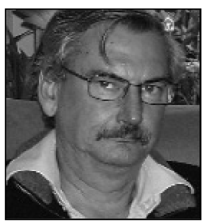
Håkan Rosenqvist has worked a great deal on the economic issues concerning various energy crops, and written theses on calculation methods and economic aspects of Salix growing. He is now a researcher and consultant and works for the Department of the Environment and Energy Systems at Lund University and the Department of Plant Growth Ecology at the Swedish University of Agricultural Sciences.

Plastics direct from the field?

Agricultural crops should be used as raw materials for the chemicals industry rather than for energy production, according to Leif Bülow and Sten Stymne. We should concentrate on replacing the eight percent of fossil oil that goes to the chemicals industry with competitive agricultural products. We might in future see industrial beet and energy forests that also produce vegetable oils – or maybe even plastics?



Leif Bülow, Department of Chemistry, Lund University



Sten Stymne, Department of Plant Breeding and Biotechnology, Swedish University of Agricultural Sciences, Alnarp

Fossil oil reserves are becoming scarcer and more expensive, while global oil consumption is increasing. The battle for oil assets is unleashing wars and conflicts. Carbon dioxide levels in the atmosphere are at levels which are causing our planet to heat up at an alarming rate. Most people nowadays agree that we can no longer carry on exploiting the oil, coal or fossil gas from the earth's crust in an unrestrained fashion.

Plants become the new factory

What, then, should we do? Plants, in the form of agricultural crops and forests alike, are exciting and interesting alternatives. Raw materials from plants can be used to manufacture plastics and also packaging and furnishing materials, and even to build houses. Technical oils and products which exploit the exceptional strength of plant fibers can also be used in various contexts. Plants have a unique capacity to produce important building blocks which we can in turn use to create products with high refining values. We must therefore get used to a new image of society in which we associate agriculture not only with food production but also with the chemicals industry. Within the political arena, it is beginning to be argued that we need to develop a biobased economy in which agriculture and forestry provide the necessary raw materials instead of oil. A large proportion of conventional chemical factories may in future be replaced by processes which take place within the individual plant. The plant is becoming the new factory, the 'green factory', which obtains its energy from the sun and its building blocks from water and carbon dioxide.

Plants have hitherto been used chiefly in the production of bioenergy and new fuels. Investments in Sweden include ethanol production from wheat, ethanol production from forests, biogas production from organic waste, and biodiesel from rapeseed oil. A number of calculations have also been carried out concerning scope for replacing oil for energy purposes with biological raw materials. From a Swedish perspective, we would have to replace oil equivalent to 130 TWh with biomaterials from forestry and agriculture. Sweden currently has 22.7 million hectares of forest and 2.7 million hectare of arable land. The productivity of agriculture is substantially greater than that of forestry so even if the area available were to be reduced, arable land could, as an oil substitute, therefore meet a significant element of total energy needs. Fields and arable land taken out of service and not covered by forest could be used to grow energy crops and energy-producing deciduous trees over an area of 300 000–500 000 hectares, which would not jeopardize Sweden's food supply.

However, it is unclear that the energy sector is the one which, besides the food sector, should primarily be supplied with raw materials from agricultural land. The changeover from a petroleum-based economy also entails the introduction of biobased technology within a sector that has previously not used it, namely the chemicals and materials industry. As we show below, we believe that what we currently harvest from agriculture would be considerably better employed in the chemicals and materials industry than for energy production.

Black oil and green oil

Vegetable oil is the plant product that is chemically most similar to fossil oil. Many present-day plants produce large quantities of oil which are mainly used as an energy reserve in seed germination. The use of vegetable oil as a fossil fuel substitute has a considerable advantage over ethanol or other liquid fuels produced from sugar, whether the sugar is free or bound in starch or cellulose. The energy loss in converting vegetable oil to biodiesel is very small compared with converting, for example, starch to ethanol (Figure 1). The Figure takes account only of the actual conversion of biomass (vegetable oil and starch) to energy carriers (biodiesel and ethanol). It does not take account of the entire system from the field to end use, and thus disregards energy efficiency per area unit. This is highly dependent on the crop. For example, rapeseed has substantial energy inputs in the cultivation process, and so, when considering energy efficiency per unit area, it is therefore less significant that the energy losses

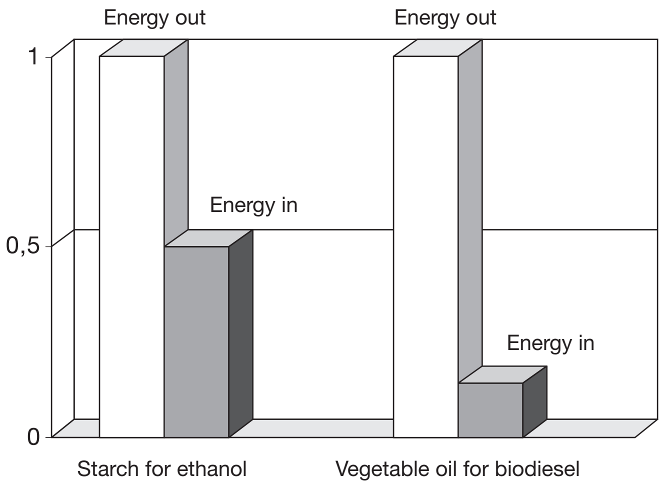


Figure 1. Energy extracted and introduced in the production of ethanol from starch and biodiesel from vegetable oil (values from a number of international sources).

are small for the conversion of rapeseed to biodiesel compared with the conversion of wheat starch to ethanol.

Total production of vegetable oil from global agriculture is roughly 125 million tonnes per annum. This may seem a high level, but is equivalent to less than 3 percent of total annual consumption of fossil oil. Currently, around 15 percent of vegetable oil (i.e. 0.5 percent of annual fossil oil consumption) is for technical applications, while we eat the rest. By how much can we therefore raise production of vegetable oil to replace fossil oil? We must count on using at least 85 percent of current production for food, and this quantity must increase with population growth. Over the last 20 years, the production of vegetable oil has doubled and can probably be expected to double again over the next 20 years through higher yields and increased areas under cultivation. Despite this sharp increase in production, this could replace only 3 percent of the fossil oil we consume and around 6 percent of the vehicle fuel we currently consume globally.

Drought-tolerant oil plants in tropical lands

An interesting option for further boosting production of vegetable oil is the cultivation of drought-tolerant oil plants on land that is not currently productive. One such plant, *Jatropha curcas*, is now attracting great interest. This perennial tropical bush is extremely adaptable and, with a good nutrient supply and high levels of precipitation, provides an oil yield per hectare on a par with the oil palm, i.e. 5–8 tonnes. Of more interest is the fact that it also copes on very dry land on which no agricultural crops can grow, yielding as much oil as rapeseed per hectare. It can even survive for two years without any precipitation whatsoever.

As the oil-rich seeds are toxic, the Jatropha plant cannot be used for food, but is ideal for biodiesel. Traditionally, it is used for making soap and candles. National programs to plant Jatropha on millions of hectares of marginal land are now being undertaken in tropical lands. In China, the plan is to plant Jatropha over an area the size of England, i.e. 13 million hectares, by the year 2010. The plantations are expected to produce 6 million tonnes of biodiesel per annum, or 30 percent of China's renewable energy by the year 2010.

If the plant delivers what it promises, it should alone be able to contribute to production equivalent to current vegetable oil production while at the same time making a substantial improvement in both economic and climatic aspects in drought-afflicted tropical lands. Together with the increase in production from traditional land, we could therefore replace 12 percent of global fuel consumption with vegetable oil.

Oil-rich trees with gene technology

In Sweden, around 100 000 tonnes of rapeseed oil is produced each year. It might be thought that rapeseed is the plant from which the most oil is extracted in Sweden, but this is not the case. Sweden produces three and a half times as much oil in the form of fatty acids in its pulp industry in the form of "tall oil" from trees, despite the fact that trees contain only approximately 1 percent oil. Tall oil thus offers significant potential for biodiesel production in Sweden. Sweden is the leading pulp producer in the world, and yet total production of 'tree oil' is of the order of only 2 million tonnes. Current tree oil could make only a marginal contribution to the global vehicle fuel supply.

It is conceivable that, with the aid of gene technology, we can boost the oil content of our trees very considerably. For example, there is a Mongolian tree containing up to 10 percent oil in its wood. We assume that we can develop an energy tree containing 10 percent oil: willow or poplar in our latitudes and eucalyptus in more southerly countries. Our research team in Alnarp in southern Sweden has just started a joint project with Umeå Plant Science Center in northern Sweden with this aim. We might then be able to extract around 60 million tonnes of such oil globally per annum, which would make a net contribution of 3 percent of the vehicle fuel supply. The advantage of this oil should be that, like tall oil, it would be very inexpensive to produce compared with oil from agricultural crops. Trees require very little energy input during cultivation and felling, and the oil becomes a by-product of the wood, which constitutes the main economic asset of the crop.

Were all these scenarios to materialize, we could replace 15 percent of our vehicle fuel with vegetable oil. In other words, we would have 85 percent of the problem left. Of course, we will also use other plant products as vehicle fuel, such as starch and cellulose, but converting these to liquid fuel is significantly more demanding in terms of energy. Even if we make the most of the large quantities of cellulose that exist in what we currently usually plough in (straw and haulms), this also calls for an expansion of production in a similar way to what we have outlined for vegetable oil – so that we can continue to supply the food and materials sectors with the raw materials needed.

Fantastic organic chemists

Plants are in fact not particularly effective at converting solar energy into energy that is usable for us. The simplest photoelectric cells yield significantly more energy per unit of light than what we can extract by tapping the energy found in the carbon and hydrogen compounds present in plant material. On the other hand, plants are fantastic organic chemists which can produce the most intricate organic molecules. It is in this respect that plants have a competitive advantage over fossil oil.

Before the First World War, biological raw materials dominated the chemicals industry. Rising food prices, cheap mineral oil and the development of organic chemistry prompted a shift to fossil oil as the dominant raw material. However, within certain sectors in which the chemical structure of the biological raw materials was well adapted to industrial applications, these raw materials retained their position, despite the fact that the price of the organic raw material was much higher than the price of fossil oil. Fifteen percent of vegetable oil is currently used in industrial applications because it is advantageous in terms of cost. You can also make soap from fossil oil, but then you have to build an entire petrochemical plant. Place coconut fat in a sodium hydroxide solution and heat – and soap rises to the surface!

Sugar – a new raw material for plastic production

Plants suitable as raw materials for use in industry are currently being developed and improved by breeding. Besides vegetable oils, sugar is a highly suitable raw material for industrial production. Sugar can be fermented into ethanol, but can also be used for fermenting into many other products. Instead of ethanol, we can for example produce lactate or propandiol, which are suitable raw materials for plastic production.

The sugar can be produced from sugar cane, as in Brazil, or from sugar beet, as in Sweden. Sugar beet is one of the plants best able to convert solar energy to sugar via photosynthesis. The yield from sugar beet is around 50 tonnes fresh weight per hectare. This is significantly higher than with equivalent productivity in the forest. The sugar-making industry in the region of Skåne employs around 10 000 people and thus constitutes a larger overall labor market than, for example, Sony Ericsson which, with its global presence, employs a total of 7 000 people worldwide. As a result of deregulation within the EU, prices for individual growers will be adversely affected. However, this scenario is counteracted by the fact that the world market price of sugar has been governed to a very large extent by the price of ethanol, which is shooting up. It is therefore very likely that beet growing in Sweden will, despite everything, continue to be competitive in future.

The total area available for beet growing in Sweden is 360 000 hectares. Half of this is currently utilized, and as we have a four-year crop rotation sequence, this is equivalent to a cultivation area of approximately 45 000 hectares. As sugar beet growing is so vulnerable to competition, demands for even greater harvests have been great. The improvement of traditional sugar beet into industrial beet by breeding is currently taking place at breakneck speed. Within ten years, the yield will be much greater and tolerance of drought and low temperatures considerably better.

In terms of technology for plastic production, it is important to develop a simplified process in which the traditional leaching of the sugar out of the beet can be skipped, and in which the process can be carried out with beet all year round. This is a challenge because whole beets cannot be stored for more than a few months without suffering excessive loss. As things currently stand, the sugar refineries are therefore run for three months of the year. This should be compared with the competing product of sugar cane, in which the process time is around seven months. Many other options are currently being tested to improve the situation. In Lund, we have for example evaluated a sugar beet meal which consists of dried beets. The meal is a suitable raw material for the production of bioplastics. It undeniably offers a number of interesting scenarios for the future, although several other storage methods should be developed. Ensilage or pressing of the beets into beet juice is another exciting possibility. There are also a number of new beet varieties with better stability that are already finding their way onto the market.

In the case of ordinary plastic, a great deal of energy is expended during manufacture. What is the situation as regards bioplastic? Is less process energy consumed in making bioplastic than in making fossil plastic? And how do things turn out if the entire chain is taken into account, from the oil source or field to the finished plastic? There is no clear answer to these questions. It depends on what type of plastic is involved. But the good thing is that we can obtain a bioplastic with identical properties to the fossil plastic. We can also produce the plastic directly within the plant with plant biotechnology. In the long run, this is the ultimate solution.

Moving the chemical factory into the plant

Around eight percent of all fossil oil goes to the chemical industry. Cracking this oil and building up the desirable chemicals consumes a lot of energy, usually far more than the finished products contain. The plant can build up a lot of these chemical structures itself and thus minimize the costs of further processing. Gene technology opens up special opportunities for changing the biosynthesis in agricultural plants to make products that are desirable for us. We are moving the chemical factory into the plant!

Let us focus on replacing the eight percent of fossil oil that goes to the chemicals industry with competitive agricultural products. The advantage here lies not only in the fossil material that is replaced but also in a substantial saving in energy for making the finished products. As we have shown, replacing 'only' 8 percent of fossil oil with plant products represents a major challenge that calls for new plants, new production methods and greater areas for cultivation, but lies within the bounds of possibility. Might we in future see industrial beet and energy forests that also produce vegetable oils – or perhaps even plastics?

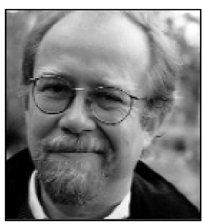
Leif Bülow is Professor of Pure and Applied Biochemistry at Lund University. His research specialism is gene technology with a special focus on modification of the metabolism of bacteria and plants.

Sten Stymne is Professor of Plant Breeding, with a focus on biochemistry, at the Swedish University of Agricultural Sciences in Alnarp. His research field is regulation of

the quality and quantity of seed oils for the development of oils, particularly for industrial use. Gene technology is an important tool in this work.

Getting bioenergy and nature conservation to go together

How does increased bioenergy production go together with the conservation of biodiversity? Major problems can arise if we merely add the production of bioenergy to what we already have in terms of food, timber and pulpwood. But this must not happen, writes Urban Emanuelsson, who presents a strategy with four main prongs. One prong entails devising new systems that generate high levels of both bioenergy and biodiversity. Another instead entails producing bioenergy intensively on certain land and biodiversity on other land.



Urban Emanuelsson, the Swedish Biodiversity Centre, Uppsala

Sweden has large areas of forests and many farms that are only just profitable. At the same time, we are very conscious that continued use of fossil fuels is harmful for the environment. It is therefore completely logical to invest in a substantial increase in Swedish bioenergy production.

But how does increased bioenergy production go together with nature conservation and the preservation of biodiversity at gene, species and landscape level and in terms of ecological processes? There is nowadays, for example, great awareness of the significance of species for maintaining vital functions for human society.

Strategy with four main prongs

Increased bioenergy production can certainly become a very major nature conservation problem if such production is merely placed in a traditional manner "on top of" existing production of food, timber and pulpwood. But it is precisely this that must not happen! The battles against two major environmental problems, i.e. the threat to biodiversity and the threat from the greenhouse effect, must not compete for resources and priorities. There is a high risk that completely different researchers, politicians and administrators will be involved on the two issues. We therefore need to launch a strategy comprising four main prongs.

Firstly, land use can in broad outline be planned in the landscape so that areas specially suited to bioenergy production can undertake such production effectively. In a similar way, the landscape must also be broadly planned so that areas with valuable biodiversity must not be used for such bioenergy production if this impairs biodiversity. A number of control measures should be devised to allow such a strategy.

Secondly, continued adaptation of food and timber production must take place in such a way that another step can be taken towards these "normal" sectors becoming better at conserving and sustainably using biodiversity. This may entail a certain loss of production; at the same time, however, this loss may become easier to bear if there is scope for greater bioenergy production in other areas. This part of the strategy is probably a relatively "inexpensive" way for the forestry and agriculture sectors to make more room for bioenergy production within the landscape.

A third substrategy entails assuming the bioenergy cultivation systems that already exist and then developing them in a targeted fashion so that they can assume significant value for biodiversity. This may, for example, involve modifying cultivation systems for fast-growing deciduous trees.

The fourth and final prong of the strategy entails virtually recreating or modifying cultivation systems that produce both fuel and a form of biodiversity that is more attractive than what existed before the modification took place. This may, for example, be relevant in the case of wetland-like areas.

New production systems must be devised

These four substrategies call not only for extensive development work but also for research. The great challenge is that the work does not belong within existing authorities or the research community. Authorities and researchers who have hitherto worked on bioenergy production have had an approach very similar to that which traditional production researchers had to agriculture and forestry. Consequently, biodiversity has normally been dealt with only very superficially.

Things are similar in traditional nature conservation research. Bioenergy production systems have only been studied by a few nature conservation researchers. What is needed is therefore not only the development of intensive co-operation but also development and research work that is markedly engaged in “inventing” systems that produce a great deal of biodiversity and energy. This is a challenge that researchers and the authorities did not seriously face before.

Designing specific land use systems and management systems is a challenge for researchers. Designing systems of control measures is in large part a challenge for the authorities, but in collaboration with user organizations and researchers. Such work is very complicated. One difficulty lies in the sectorized legislation in which systems of control measures, e.g. in terms of forest and agricultural land, look very different. Control measures also often have a specific end in view, something which even now is a major drawback, for example in terms of co-ordinating leakage control, stimulating biodiversity, the cultural environment and recreation. If control measures aimed at increasing bioenergy production without reducing biodiversity as a whole are also to be achieved in future, a great deal of innovation is needed in relation to co-ordination of the various systems of control measures.

Intensive cultivation of certain areas of forest

Within the forestry sector, a debate is currently going on concerning the intensive cultivation of forests within certain areas of the landscape. The bioenergy debate fits in with this debate. Up to now, non-profit-making conservation organizations and conservation authorities have in principle opposed such a trend. The reason has been that intensively managed farmed areas would mean a departure from the principle of reasonable consideration of nature conservation throughout the forest. So why should the fact be applauded that a number of forested areas risk becoming even more impoverished in terms of biodiversity than they are already?

If, on the other hand, there had already been a system for "swapping" increased production in certain areas for higher levels of biodiversity in other areas, the system could probably be tested with the aim of achieving retained and perhaps even increased biodiversity within the overall landscape while also increasing overall production. A specific problem that severely works against the development of such a system is the fact that it is often not the same owner who deals with the prospective intensively farmed areas and the areas that are interesting with a view to biodiversity. There are grounds for further investigating scope for swapping production increases in very unimportant forests for increased protection and greater consideration in other forests.

Another set of problems that should be studied concerns forests in southern and central Sweden which are rooted in a landscape of pasture and agriculture. Such forests often have actual or potential nature conservation value. In the case of nature conservation, the simplest protection solution has for the most part been "free development". This solution is nowadays called into question both by nature conservation researchers and researchers of cultural history. Lost biodiversity and reduced cultural history value can in many cases, though by no means all, be the consequence of free development. Some extraction of timber may, in some cases, well lead to forests' improved retention of value in terms of biodiversity, cultural history and recreation. Some research on this is already being conducted, but the nature conservation side and the production side should be better co-ordinated.

Wetland grass, energy grassland and energy forests

In the agricultural landscape, the questions are somewhat different. Here, it is much clearer in a number of cases that energy production focused in the right way can yield a number of other positive environmental effects. For example, various trials have been going on for about twenty years, albeit on a small scale, on combining nutrient reduction with energy production and increasing the biodiversity of a landscape. This entails existing or newly established wetlands in which haymaking can bring about riparian meadow-like environments that are valuable for a number of threatened wetland organisms, not least waders and ducks. The trick is to find the right sort of grass or sedge vegetation that can be used for nutrient reduction and for bioenergy production as well as having a positive impact on biodiversity.

On farms with natural pasture-based beef production, production of energy grassland could be versatile. In years of poor pasture and grazing production, the energy grassland could be incorporated in meat production, while this grassland could, in productive years, be exploited for bioenergy production.

Agricultural crops and wetland crops have a problem in terms of harvesting, storage and extraction of the energy. Timber crops therefore often have a short-term advantage. However, the products of agricultural land and wetlands have an inherent flexibility that can be of great value for nature conservation and the maintenance of culture. A specific problem that concerns agricultural land for bioenergy production is where any fast-growing trees such as willow and poplar should be placed in an agricultural landscape.

Planning – with a private initiative

Cultural environment and recreational values are very important within the landscape. The physical planning system and relatively strong control measures are needed when handling bioenergy production in the country in a responsible fashion in accordance not only with the values of nature conservation but also with cultural environment values and recreational values. At the same time, however, private initiative must be protected and stimulated. This is not an easy balancing act to achieve. Ecological landscape planning in forests can be seen as one of several sources of inspiration, as can a number of successful local authorities in which town and country planning has worked well, for example Kristianstad with its Vattenrike facility and Örebro with its extensive restoration project.

Current environmental work in Sweden is governed in an overarching manner by sixteen environmental aims.

The system has proved successful and provides a clear focus in environmental work. Calling these environmental aims into question is therefore not an especially constructive strategy. On the other hand, conflicts arise between different environmental aims, not least between those concerning climatic impact and biodiversity. It is therefore very important for continued credible environmental work that substantial efforts are made to develop the control instruments and specific land use.

Urban Emanuelsson is Professor and Director of the Swedish Biodiversity Centre in Uppsala. He is a plant ecologist specializing in cultivated land and issues concerning historic ecology. He is also involved in environmentally oriented social planning and international work focused on Europe and other locations around the world.

What do we need forests for?

Forests are a limited resource that must stretch to more and more applications. Not least the demanding aims set out in the environmental objectives of "Limited climate impact" and "Living forests" will lead to conflicts of aims between nature conservation, climate measures and the forestry industry. Clear winners in this scenario are those who own forests and can enjoy ever higher values for their forests.

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Photograph: AnnaKarin Drugge

Sweden is a land of forests, with more than half its surface area being covered by birch, spruce, pine and other types of tree. Forests constitute a natural resource which has contributed in many ways to prosperity and well-being. A lively debate is currently being conducted concerning how we should best use forests. Energy conversion, climate change and scope for using forests with the aid of new technology are relatively new issues on the agenda. At the same time, the forestry industry is still a cornerstone of the economy, a bright future is predicted for sawmills, and new biomass-based district heating power plants are being built in a number of municipalities. Over the last fifteen years, fossil fuels in the district heating plant sector have largely been phased out and replaced by biomass fuels, particularly forest fuels. The same applies to the heating of small buildings. On the agenda now is the replacement of fossil fuels with renewable fuels produced by, in particular the agriculture and forestry sectors in Sweden.

The Oil Commission appointed by Swedish Prime Minister Göran Persson set itself the aim of cutting levels of petrol and diesel consumption in the transport sector by 40–50 percent by the year 2020. A change of this kind is a significantly greater task and challenge than the change that we have seen on the heating side. A rough calculation shows that if such a large proportion of fuels is to come from forests, virtually all current forest production must be taken into service for fuel production alone. At the same time, one of the environmental aims means that large swathes of forest must be set aside for nature conservation in order, among other things, to preserve biodiversity in the forests. In parallel with this, we can see that rapid and substantial progress is being achieved within biotechnology and materials development. Among other things, trials are going on concerning the use of tree-based products within surgery, and one day your car may be largely made from trees.

Hard values and soft values

Will Swedish forests stretch to all this? Instead of thinking about the question in physical terms (how many cubic meters are there?), we assume a socioeconomic perspective here. This means that we should use forests in such a way as to maximize the socioeconomic value. We should explain what is meant by the socioeconomic value of forests, how this can be measured, and what current conflicts of aims may be considered to entail for the future. It is important to understand that we use the term 'socioeconomic value' to mean anything that can in any way contribute to prosperity and well-being. This means that the forest's "softer values" have just as much importance on the market as the forest's "harder" values. It need not be "more" socioeconomically profitable to make paper from a tree than to conserve it. What is most profitable depends quite simply on how we rate the various applications in relation to one another.

But let us start by pointing out that questions concerning the use of forests are by no means anything new. The Swedish scientist Carl Linnaeus (1707–1778) suggested in connection with his Lapland journey that forests not used for material things were largely worthless: “Large forests of pine stand desolate and idle because nobody needs the timber, and fall down and rot away. Would they not deserve to be made into tar and pitch?” Natural philosophers, on the other hand, such as Henry David Thoreau (1817–1862), thought that every community should allow itself forest in which “not a twig should be broken”, for educational and recreational purposes. Then as now, market economics values are set against conservation values and other “softer” values associated with allowing the forests to remain in place.

The timber price does not reflect many of the values of trees

What, then, is meant by the value of forests? The value of forests for Linnaeus was the “forest products” they yielded in terms of timber, pitch and tar, whereas Thoreau clearly considered that undisturbed forests were of great value. Often, we may think of value in terms of a price; a high price means a high value and vice versa. However, the concept of value in modern economic theory is linked to subjectively experienced utility. This means, for example, that goods or services that are not priced on a market can yield great utility. Goods with a low price can also be very valuable. We derive great utility from water, even if the price of water in Sweden is low.

Only in a perfect market economy does the price of timber reflect all values of a tree, not just the value of timber. In real-life Sweden, market prices do not therefore always provide a full picture of a resource's socio-economic value. To gain a more complete picture, we must try to measure the immeasurable and place a value on the various benefits we derive from the forests which lack a price (but not value). We will return, for example, to such calculations.

How have forests been used?

The relative importance of the various applications of forests has changed over time, as needs (utility) have changed, though also in line with technical scope for converting the raw materials of trees. Use in the forestry industry really got going at the end of the nineteenth century at the same time as industrialization, even if firewood dominated use until the beginning of the twentieth century. Forests have always been important as an energy source, not least during the First and Second World Wars, when the supply of imported energy was curbed. However, ever cheaper oil in the 1950s and the harnessing of the rivers in the 1950s and 1960s meant that forests assumed less and less importance for the supply of energy.

The development of forestry policy clearly follows the pattern for use. Its original task was to ensure that forests would exist even in future. Gradually, forestry policy took on an industrial slant; it was designed to ensure that the forestry industry was guaranteed raw material. The latest major changes in forestry policy reflect social changes in that the environmental aspect is increasingly in focus, but also as a result of forestry conservation having become ever more minutely regulated.

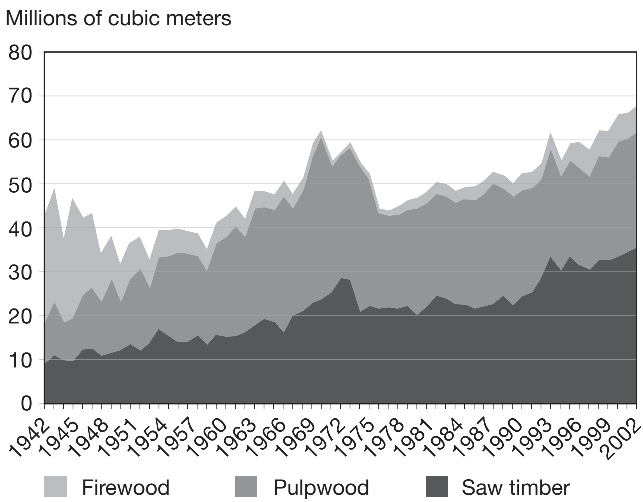

Figure 1. Felling levels in Sweden over the period 1942–2004. (Source: the Swedish Forest Agency)

Figure 1 shows how felling levels have evolved since the beginning of the 1940s and provide a breakdown of felling across the three main ranges of product, namely saw timber, pulpwood and fuel wood (fuel wood includes only stemwood). All in all, we find that total felling levels have increased from approximately 50 million cubic meters in 1942 to nearly 70 million cubic meters in 2004. Besides the post-war decline and the substantial decline in connection with the first oil crisis in the mid-1970s, the trend for felling levels has been upwards. The Figure also shows that there was a clear shift from fuel wood to pulpwood and saw timber up to the mid-1970s. It is interesting to note that fuel wood has increased its share significantly since the mid-1970s. This reflects, of course, the fact that the value of forest as an energy source has increased.

Putting a price on soft values

We can measure the values associated with Figure 1 relatively easily with the aid of market prices. However, they do not capture the total evolution of value in forests; we must add the values that are not "visible". A large number of studies are available concerning the contribution made by forests to "green" national product. In the USA, it has been calculated that market-priced goods and services from the forestry sector account for 20 percent and that recreational, hunting and other "green" services account for 80 percent of an expanded national product for forestry.

One of the very first attempts to estimate the value of Swedish forests more broadly was made by Lars Hultkrantz in 1992. An update and expansion of his calculations was carried out later by Peter Eliasson (in 1994), who also calculated changes in the various values of forests between 1987 and 1991. In these calculations, the values of the forests are divided into three different groups: timber values, other production values and environmental assets. The first two values can be regarded as flow values, while the last one is linked to supply, i.e. the stock of forests and forest land. Perhaps the most interesting thing is that it has been attempted to assess all utilities in monetary terms by assuming people's subjective evaluation in studies of willingness to pay.

Recreational value and carbon dioxide binding

Other goods production – berries, mushrooms and meat – contribute in very small part to the total added value of forests. One reason for this is that the values presented do not include recreational values. A none too daring guess is that the recreational values associated with mushroom and berry picking and hunting is considerable. In addition, other recreational values linked to forests are not available. For example, Swedish studies are available which show that the recreational value of elk hunting is nearly twice the value of the meat.

Another and significantly more important service that forests provide when they grow is to bind carbon dioxide, i.e. the forests take up and store carbon dioxide from the atmosphere. The value of this service is, according to the calculations, several billion Swedish kronor a year – comparable with the added value in Swedish forestry, which is around 20 billion SEK.

There are a relatively large number of studies in which it has been attempted to measure the recreational value of forests. In Sweden, direct willingness-to-pay questions have, for example, been used to identify the value of modifying forests in a more recreationally friendly manner. Non-Swedish studies put the value somewhere between SEK 180 and 350 per recreation day, and this tallies relatively well with Swedish studies. The value of hunting is in the upper part of this range, and walks in the forest in the lower part. If this value is summed for the number of person-days in the forests, it is apparent that the total recreational value is significant, and that very small changes in the forests' facilities for recreation can have relatively major consequences for the total value.

These examples show that there can be significant value in forests, even if this is not always apparent on the market. The examples also show that, in general, there is a "trade-off" or alternative use for forests; if we alter forest management in a certain direction, for example to produce more bioenergy or timber, we must "pay" in cases where there are losses of other utilities that the forests provide. It should be pointed out, however, that in some cases the production of other utilities can increase as a result of more intensive forestry, for example raspberries in forest clearings.

Do the forests stretch to everything we want?

The question of whether the forests "stretch" cannot be answered simply. What we can say is that greater use of forests to achieve a specific aim increases the cost of achieving other aims related to forests; the costs take the form either of increased fertilization or other measures to promote growth or of lost environmental value. The conflicts of aims have in a way been relatively limited until the present day. Forests have been seen as a source of raw material for industry and energy, and modern high-yielding forestry has succeeded relatively well in supplying inexpensive raw materials to industries that compete to some extent on raw materials.

That time is now thought to be at an end. The bioenergy revolution that has taken place over the last fifteen years within, above all, the district heating sector has been possible thanks to relatively minor raw material conflicts with the traditional forestry industry. The district heating sector's substantial replacement of oil and coal with forest fuels has probably been possible thanks to low costs of by-products from forestry, which is in large part a consequence of the forestry industry's continued expansion. Nevertheless, there is a great deal to indicate that further expansion of a larger-scale nature is impossible without greater competition or conflicts of aims. The environmental target of "Living forests" means greater areas of production-protected forest at the very time that increased demand for bioenergy, and thus higher prices, make it interesting to burn and distil pulpwood, and perhaps even saw timber.

Appreciate the utility of forests!

The different values of forests change over time; certain values decrease in importance while others increase. Forests have assumed an ever more multi-facetted role for our welfare, and this will mean steadily growing difficulties in meeting more and more aims for little sacrifice. If we want greater economic or material benefits from the forests, it is not quite so simple for us to have a great wealth of species or pleasant forests for recreation – and vice versa.

The complexity arising from the forest values makes great demands of the knowledge required to take decisions that are socioeconomically effective and judicious. What is socioeconomically effective and judicious use of the forests depends quite simply upon how citizens rate the utilities that we can obtain from the forests. What thus emerges as being of key importance is an evaluation of forests' various utilities and, with the aid of these values, an impact assessment of various proposals concerning our use of the forests. These calculations must of course be conducted from a broad perspective of forest values. Among other things, this means that we must understand how the various parts of the forest sector interact with one another.

With the current focus on alternative use of forest raw materials, there is little to indicate that we will in future exploit Sweden's forests in the same way as over the last hundred years. Whether this is good or bad for Sweden, we cannot answer here.

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Bioenergy from the forest – pluses and minuses for environmental aims

If we extract biomass from the forest for use as energy raw material, this promotes one of Sweden's sixteen environmental aims, namely "Limited climate impact". And biodiversity tolerates increased removal of branches and tops in connection with felling, writes Gustaf Egnell. At the same time, the increased extraction may have consequences in the form of more acidic soil and water, thus posing risks to fauna and flora. Recycling wood ash can be a way of raising the pH of surrounding water in the long run.

Gustaf Egnell, Faculty of Forest Sciences, Swedish University of Agricultural Sciences

Increased use of biomass from forests for energy purposes helps Sweden achieve one of its sixteen environmental quality aims, namely "Limited climate impact". A secondary aim is, over the period 2008–2012, to reduce emissions of greenhouse gases to a level on average 4 percent below levels in 1990. At the same time, greater use of biomass from forests may affect a number of the other environmental quality aims, including several in an undesirable way. Successfully increasing the level of bioenergy derived from forests therefore requires that all stakeholders involved agree on reasonable levels of use and thus a reasonable balance between various environmental aims. As other energy alternatives (fossil fuels, nuclear, hydroelectric and wind power) also have negative environmental effects, this must also be considered in such an assessment. The most environmentally friendly option is always to increase energy efficiency.

Many species are dependent on dead wood

A number of the environmental quality aims are clearly linked to biodiversity. Those directly linked to increased extraction of biomass from Sweden's forests include "Living forests" and "Rich plant and animal life". An estimated 7 000 species in Sweden are dependent on dead wood of various grades. A common denominator for many forest species considered to be rare or threatened is the dependence on dead wood. This is an important reason why one of the secondary aims for the environmental quality aim of “Living forests” is formulated in the following terms: “the quantity of dead wood must increase by at least 40 percent throughout the country and by considerably more in areas where biodiversity is specifically threatened”.

One reason why so many of the species dependent on dead wood are rare nowadays is probably that forestry has for a very long time focused on a single aim, namely to build up stocks of wood and supply Sweden’s forestry industry with fresh softwood. The forests have been managed so that few trees within the stands have died, and final felling of the stand takes place well before the end of the tree’s biological life time. Forestry has in this way increased the standing stock in Sweden’s forests substantially (Figure 1).

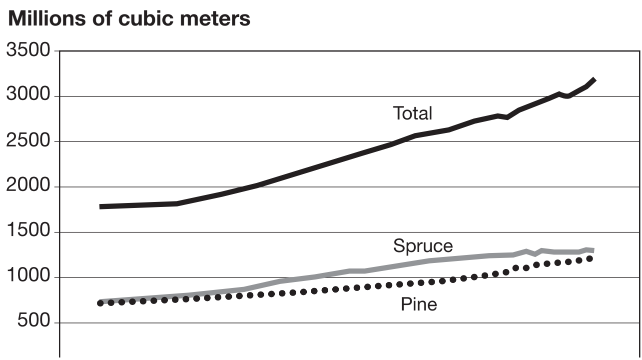

Figure 1. Changes in total standing stock and stocks of Scots pine and Norway spruce in Sweden over the period 1926–2003. (Source: National forest survey, Swedish University of Agricultural Sciences)

A lot of dead wood is left over from felling

When we harvest timber and pulpwood in these wood-dense forests, large quantities of fresh dead softwood remain in the form of branches, tops (harvest residues), and stumps that could be used for energy purposes. The increased stock of timber together with active silviculture has meant that the forests nowadays supply more harvest residues and low stumps than in the past. What is lacking is chiefly whole dead trees (both standing and lying), high stumps and trees that have been allowed to age. The great potential for energy purposes can therefore be tapped where the quantity of dead wood has actually increased over the last 80 years. A reasonable assumption is therefore that many species that specialize in these wood qualities have been promoted by forestry rather than the opposite and are thus relatively common nowadays. With the exception of a few thick tree tops and branches, stumps and harvest residues are not included in the statistics collected to establish whether the quantity of dead wood is increasing in our forests. This shows that great importance has not been attached to harvest residues and stumps in terms of biodiversity, although knowledge is limited.

As a result of weather and wind snapping off tree tops and branches, these wood qualities are continuously provided in our forests during a rotation period. This, even if we extract tree tops and branches at harvest,

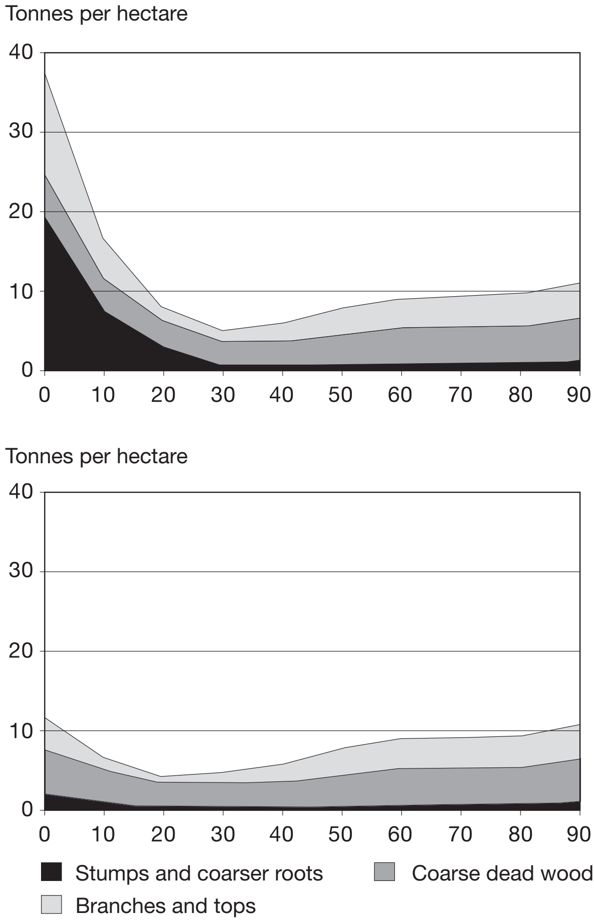

Figure 2. Skeleton diagram showing the supply of various fractions of dead wood after final felling and 90 years ahead in a spruce stand in central Sweden, both where no forest fuel is harvested (upper diagram) and where 70 percent of branches and tops and 90 percent of the stumps are removed during final felling (lower diagram).

there will be a lot of such wood qualities supplied in our forests (Figure 2). This indicates that diversity tolerates harvesting of much of the harvest residues in connection with felling. Softwood stumps, in which interest has just arisen, are supplied virtually solely at harvest. Harvesting a large proportion of the stumps in final felling leads to a sharp reduction in stump wood qualities throughout a rotation period (Figure 2). The only potential contribution during a rotation will be stumps left for one reason or the other and stumps after thinning operations, primarily smaller stumps. It is therefore reasonable to assume that a larger proportion of the stumps should be left in the forest than is the case with harvest residues, in order to promote biodiversity.

Dead wood has different qualities

A common perception is that the forestry industry has long invested unilaterally in Scots pine and Norway spruce at the expense of other tree species that may be more valuable for biodiversity. The national forest survey data provide a slightly different picture (Figure 3) in which the relative proportion of timber stock for pine and spruce has held relatively steady over the period for which data are available.

If data for certain deciduous trees are considered, it turns out that they have not decreased. As the stock of timber has increased at the same time, data show if anything

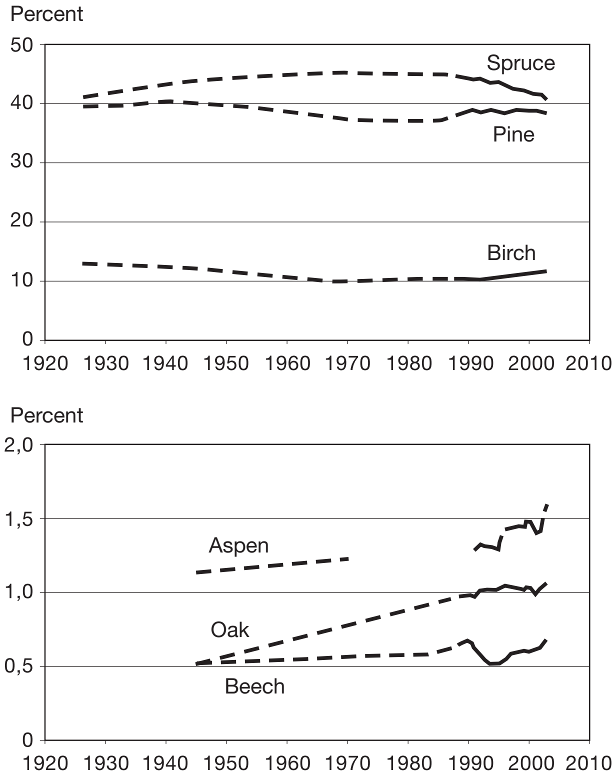

Figure 3. Proportion (%) of total timber stock for Sweden's commonest forest trees, Norway spruce, Scots pine and birch (upper diagram) and for some deciduous trees, often assumed to have been disadvantaged by production forestry for much of the twentieth century (lower diagram). (Source: The national forest survey, Swedish University of Agricultural Sciences)

that the stock of timber has also increased for aspen, oak and beech. It is therefore reasonable to assume that they now also supply more dead wood in the form of branches, tops and stumps than previously. However, this does not seem to have helped some of the rare species dependent on dead and dying wood. As recently as 2006, the white-backed woodpecker was declared to be extinct in Sweden.

It is therefore important that the aim in recent years of increasing the proportion of dead wood in Sweden's forests continues to be pursued. There is probably dead wood that is more valuable for biodiversity than young, undersized wood and stumps from our commonest forest trees. There are therefore grounds to combine aims to increase the quantity of dead wood with aims that focus more on the quality of the dead wood and thus value for biodiversity. In this work, it is also prudent to cater for other values at the same time, such as the visual landscape and the social values of the forest.

Given that forest fuel in the form of harvest residues and stumps is extracted from Sweden's forests, it is also important that there is no temptation to remove dead wood that has been left to promote biodiversity in the form of, for example, standing trees, lying trees and high stumps or snags, and that care is taken not to destroy or otherwise damage such wood. Harvest residues and stumps from tree species that are rarer in the landscape and in connection with various types of damaged forests should therefore also be left in place.

Production losses associated with extraction of harvest residues

Increasing extraction from only stemwood to include harvest residues entails a moderate increase in the extraction of wood, although the extraction of nutrients may increase significantly (Figure 4). The reason for this is that nutrient concentrations are higher in branches and above all needles as compared to stemwood.

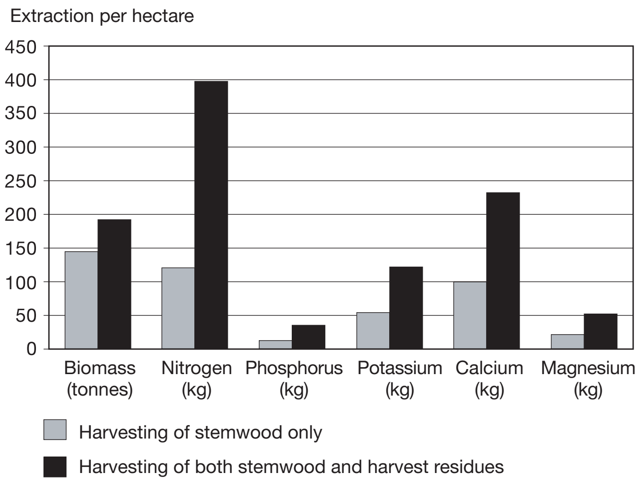

Figure 4. Biomass extraction (tonnes per hectare) and nutrient extraction (kg per hectare) for harvesting of stemwood alone and also both stemwood and harvest residues. The figures come from the final felling of a spruce stand in Halland on the west coast of southern Sweden.

This additional extraction of nutrients could lead to reduced production by our forests, which conflicts with the following objective under the environmental aim of “Living forests”: “The value of forests and forest land for organic production must be protected.” This has also been confirmed in field experiments. However, the reduction is not dramatic for extraction associated with final felling, and may be countered by soil preparation and planting being performed earlier when branches and tops that otherwise form a physical impediment have been removed.

When harvest residues are harvested during precommercial thinning and thinning (the forest is thinned by felling certain trees), nutrient compensation with primarily nitrogen is on the other hand required, in order to counteract production losses in the remaining stock. Recycling wood ash has been proposed as a means of countering this and as a step towards an ecocycle-based society. Unfortunately, the nitrogen so important for forest growth disappears with the flue gases when the wood is burned. Ash alone can therefore not counter the loss of growth completely. The addition of nitrogen is therefore required on most land despite the fact that a lot of nitrogen reaches the forest land via airborne pollution and rain.

Extraction of harvest residues makes the ground more acidic

When forest grows, the forest land is acidified – the higher the level of production, the greater the acidification burden. In addition, there is the more serious acidification of the soil caused by airborne pollution. Once the ground becomes more acidic (lower pH), water running off becomes more acidic and mobility may increase for a number of substances not wanted in our water, such as aluminum. This has in many places created problems in groundwater, lakes and watercourses that are dependent on the high quality of water running in.

Where forests are felled, nutrients with an alkaline effect (counteracts acidification) are recycled when nutrient-rich branches, needles and roots are decomposed, and the pH in the ground increases at the same time. If the nutrient-rich branches and needles are harvested, the rise in pH is not so great. Extracting chiefly the nutrient-rich harvest residues is thus not compatible with the environmental aim of "Only natural acidification".

Wood ash raises the pH of the soil

To counter first of all unwanted effects on surrounding water from forest fuel extraction, the recycling of wood ash is currently recommended by the responsible authority, which is the Swedish Forest Agency. This measure contributes to the pH of the upper layers of soil being at a higher level. Less clear, however, is whether and, if so, when a moderate dose of ash (no more than 3 tonnes per hectare is recommended) will affect surrounding water when ash is applied to various kinds of forest land. A liming program for lakes and watercourses is currently being conducted in Sweden with the same aim, namely to ensure good water quality and biological life in the water. Lime is added directly into the water or where water streams out from the soil into the watercourses. Broad application to forest land has never been considered in this program. Ash could be a useful resource in this work. One issue that has been discussed is whether ash should be applied more directly into the water where it directly does good rather than being applied wherever harvest residues have been harvested with an uncertain future benefit for water quality.

Besides the motive of counteracting the acidification of land and thus water, the precautionary principle has sometimes been cited as a reason why we should recycle ash in forest land if the extraction of nutrients increases, in the light of possible adverse effects on plants, animals, fungi and micro-organisms in the forest land ecosystem and the long-term production capacity of forests. The same principle can also be cited for not undertaking ash recycling because ash also exposes the forest ecosystem to risks if the recycling is performed inappropriately. Ash that has not been treated correctly (hardened) before application can be highly reactive and directly cause corrosion damage to terrestrial vegetation and terrestrial organisms. Among other things, mosses are vulnerable to poorly hardened reactive ash. Various kinds of environmentally harmful substances such as heavy metals and organic environmental toxins can readily slip through a system in which not all ash applied is first checked. Another problem with ash recycling is that forest production on land that is not so fertile tends to drop for a while after ash application. It may therefore be difficult to motivate the forest owner to apply ash when the supply of renewable biomass is falling.

Wood ash on peat land

At the same time, ash is a resource that should be used – but judiciously. The need to counteract acidification of our water is clear, but varies across Sweden. This argues in favor of site adaptation and regionalization of the recommendations. The ash may also constitute a resource for boosting production if used on appropriate land. Ditched peat land on which forests currently grow are such an example in which the addition of ash alone may boost forest production considerably. At the same time, ash may, purely theoretically, accelerate the microbes that control peat land's production of greenhouse gases such as carbon dioxide, methane and nitrous oxide. For ash fertilization to be a judicious choice on forested peat land, the binding-in of carbon into trees must certainly exceed any increased emissions of greenhouse gases.

Research is being conducted to identify what peat land is “risky” and how the ash should be handled and applied to minimize the risk. In addition, ash can be used together with nitrogen to increase growth on most forest land in Sweden. There is a great deal to indicate that we will need more tree biomass in the future. Not only to meet energy needs but also the forestry industry’s needs for more raw material. To achieve this, wood ash is a valuable resource together with other nutrient-rich waste products.

More intensive forestry

Judicious administration and prudent use of renewable forest raw material have the potential to contribute to the fulfillment of a number of environmental aims. Several of the other sources of energy and raw materials may, from the perspective of environmental aims, be a poorer choice. To achieve this, many of the potential environmental effects associated with increased use of all forest raw material above ground together with higher targets for raising forest production need to be studied at landscape level. It would therefore be desirable right now to incorporate larger areas in which the environmental impact of more intensive forestry can be studied at the same time as technology and logistics are being refined to supply high-quality renewable forest raw material for various processing chains within the energy and forest industry.

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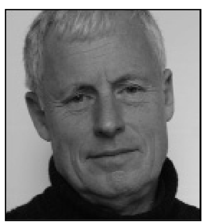
Biomass fuels not entirely climate-neutral – but better than fossil fuels

Kristina Holmgren and Mats Olsson have, together with colleagues, compiled and evaluated emission data for production and usage chains for a number of biomass fuels. They conclude that none of the fuels investigated can be called "climate-neutral" because all fuel chains result in net emissions of greenhouse gases. They also conclude, however, that biomass fuels result in considerably lower emissions of greenhouse gases than fossil fuels and that they can therefore be used to replace fossil fuels.

Kristina Holmgren, IVL Swedish Environmental Research Institute Ltd



Mats Olsson, Department of Forest Soil Science, Swedish University of Agricultural Sciences

In line with growing awareness and concern about climate change, demand has grown for new technology and energy raw materials that offer lower greenhouse gas emissions than fossil fuels. Demand for bioenergy has thus also grown. These are considered to be climate-neutral and not to contribute to increased carbon dioxide concentrations in the atmosphere. This can be justified in two ways:

- New plants and trees that replace harvested and burned biomass will take up carbon dioxide (CO_2) from the atmosphere in a quantity equivalent to that released during combustion.
- If biomass is not used as fuel, it dies sooner or later and is broken down. During the breakdown process, a quantity of carbon dioxide that largely corresponds to that formed during combustion is released.

Climate-neutral – a concept that is difficult to define

The concept of climate neutrality is applied by many despite the absence of a strict definition of the concept. It is used to refer to activities or fuels that do not lead to emissions of greenhouse gases or for contexts in which any emissions are offset by investments that cut emissions elsewhere. With current knowledge and models, we can scarcely measure or consistently describe the climatic impact of an activity; on the other hand, we can measure and assess what emissions such an activity will lead to. How the climate is affected by emissions is in part unclear and is assessed by various climate models. How the climate in various regions and parts of the world is affected and modified as a result of the elevated levels of greenhouse gases in the atmosphere also varies. For these reasons, the term "carbon dioxide neutrality" could be used instead of climate neutrality, or better still "greenhouse gas neutrality" because gases other than carbon dioxide are also involved.

In fact, there are scarcely any biomass fuel that are neutral in the sense that they result in net emissions that are zero. Emissions are released during production, transportation and use of biomass fuels, and even if these are as a rule relatively low, this means that the concept of neutrality is scarcely relevant. Situations are also conceivable in which production and use lead to net uptake of greenhouse gases.

Holistic perspective important

To be able to estimate the level of greenhouse gases induced by a certain biomass fuel, a lifecycle analysis or system analysis must be conducted, i.e. an analysis and description of all greenhouse gas flows that can be associated with the handling of this fuel during production, transportation and any other handling including use. In the case of energy forest, for example, this means that emissions arising from machinery during establishment and harvesting of the forest, production of nitrogen fertilizer and emissions from the soil and from burning are included.

How the soil is affected often plays an important part in the analysis as production and harvesting often affect its stock of carbon. A reduced level of carbon in the soil in the form of humus means that equivalent levels are supplied to the atmosphere as carbon dioxide. Production of biomass fuels may, however, also result in increased soil carbon stocks and thus a corresponding reduction in content of carbon dioxide in the atmosphere. This may, for example, apply to the production of forest on abandoned arable land. Emissions of nitrous oxide (laughing gas, N_20) and methane may also arise from the soil. The former is formed particularly as a result of nitrogenous fertilization, and the latter particularly when the soil is very wet.

System limits controversial

It is very important and often a matter of controversy how the system limits are set for the analysis. In interpreting data from lifecycle analyses, one must therefore always ask oneself how the system has been framed. An example is the use of felling residues in forestry after harvesting of timber and pulpwood. The question is whether and, if so, how greenhouse gases from establishment of the forest should be counted, or whether they should be linked to primary production in forestry, i.e. production of timber and pulpwood. One approach is that the felling residues are a by-product that must not be burdened with emissions from forestry. Another approach is that the emissions of forestry should be shared proportionally between main production and by-production. The approach adopted is important for calculating emissions of greenhouse gases and climate impact. In the summary below, we have chosen not to include emissions from forestry, but only to count emissions arising after the decision to use felling residues as fuel.

Another example of how the system limits can become crucial is in the production of energy forest on ditched peat land that has previously been used as farmland. The ditched land will emit high levels of carbon dioxide (and in some cases also nitrous oxide) as a result of the previous ditching and use. Should these emissions be debited to the emissions of energy forests? A common position is that only emissions directly linked to energy forest production are taken into account, for example carbon dioxide due to peat decomposition as a result of maintained ditches, and nitrous oxide emissions as a result of nitrogenous fertilization of the energy forest.

Decomposition takes variable lengths of time

The reference situation is very important, i.e. what would happen with the biomass if it were not used for the production of heat and electricity. During its growth, the biomass takes up carbon dioxide from the atmosphere via the process of photosynthesis and gives off the same amount when it is burned or decomposed. Harvesting of biomass entails a direct loss of carbon in the forest (the stock of carbon above ground). Burning leads to this stock being transferred to the atmosphere. If the biomass had not been harvested and burned but left in place, the same loss would arise as a result of breakdown, but this would have taken considerably longer, anything from a few years to hundreds of years, depending on the type of biomass.

To say that releases of carbon dioxide from the burning of biomass are offset by emissions that would have arisen anyway in the case of the breakdown or uptake of new biomass is therefore true only if emissions over a certain period of time are considered. The time needed differs between different biomass fuels. In the case of straw, for example, the time is short. If the straw is not harvested but is left on the field, it is broken down within a few years. Felling residues in forestry, and particularly stumps, require a substantially longer period.

Better than fossil fuels

Based on existing literature, we have compiled a summary of emission data for the production and usage chains for a number of biomass fuels. We conclude that none of the fuels investigated can be called "climate-neutral" as all fuel chains investigated lead to net emissions of greenhouse gases. However, we also conclude that biomass fuels generate substantially lower levels of greenhouse gas emissions than fossil fuels, and can thus be used to replace them.

Emissions of greenhouse gases vary for different fuel chains depending on the fuel and how the system limits are set in various studies. The following factors may make a significant contribution to total emissions of greenhouse gases in the production and usage chains for various biomass fuels: the effect of the production system on the soil carbon, soil management methods (particularly on drained peat land), use of fertilizers (both direct and indirect effect on greenhouse gas emissions), combustion technology, refining of the fuel (for example, pelleting) and storage (particularly for pulverized fuels). Other sources that also contribute to emissions in a production and usage chain are harvesters, transport and waste management.

Biomass fuels win in the long run

Figure 1 shows a summary of net emissions of greenhouse gases for the fuel chains investigated and corresponding emissions for coal and natural gas. It should be noted that emissions of carbon dioxide from burning are included for coal and natural gas while they are not included for biomass fuels. This is due to the fact that the carbon dioxide from burning biomass fuels is offset by the emissions that would have arisen if the material had instead been broken down naturally, or by carbon dioxide uptake in growing biomass that replaces that which has been used as fuel. There is nevertheless a major difference in the emissions profile between the combustion scenario and the breakdown scenario/the uptake scenario. Emissions take place directly at the combustion stage, while breakdown and uptake take many years, decades or even longer depending on which fuel is involved. This is not apparent in Figure 1, which shows a situation in which carbon dioxide emissions from burning fuels have been compensated for by breakdown or uptake. Reporting emissions in this way means that different time aspects appear for different biomass fuels in the same Figure. The result shows, however, that there is a difference in net emissions between different types of biomass fuels and that there are uncertainties in the estimates that can be improved.

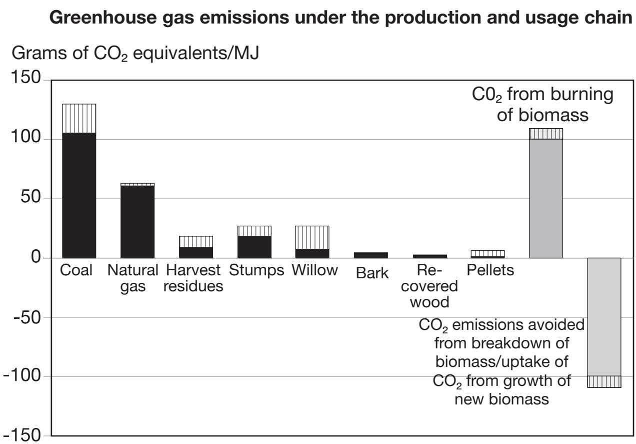


Figure 1. Comparison of emissions from fuel chains based on data from the literature. The two bars on the right show CO_2 emissions from burning and breakdown of biomass. Over a longer period of time, these two bars may be assumed to be of equal size. The striped parts of the bars show the variation between different production and usage chains of the same fuel.

The climate impact from emissions from one of the biomass fuels, harvest residues (branches and tops), has therefore also been compared with the climate impact from fossil fuels with the aid of calculations of the impact on the radiation balance. (The term radiation balance should be understood to mean the earth's energy balance, i.e. the balance between incoming and outgoing energy). These calculations include not only emissions of carbon dioxide from combustion but also emissions of carbon dioxide avoided as a result of breakdown of the biomass, taking account of the time aspect.

The calculations are set out in Figure 2 and are based on emissions during production and use of the fuel. The zero line represents the emissions that would have occurred even if the fuels had not been used. For coal and natural gas, this means that the coal or gas would have been left in the ground and not been extracted. In the case of harvest residues, this means that the cutting area residues would have been left in the forest and been broken down. This gives rise to emissions of carbon dioxide for a long time and in a quantity corresponding to the emissions released during the combustion process. The Figure shows that the harvest residues scenario in the long run levels off; its level is due in large part to the bringing forward of the carbon dioxide emissions entailed by the combustion process. Only a small proportion is due to auxiliary energy at the removal stage (processing machinery, chipping and transport) and the reduction in the ground coal stock that can be expected as a result of removal. This means that biomass fuels with a short rotation age induce less of an effect on the radiation balance than fuels with longer rotation periods provided that energy input and other aspects are the same.

The results in Figure 2 show that the impact on the radiation balance from the use of harvest residues is significantly smaller than the corresponding impact from the fossil fuels. It is not self-evident what time perspective should be adopted when assessing the impact on the radiation balance as a result of emissions. In its fourth report on climate change, the UN's Intergovernmental Panel on Climate Change (IPCC) does not provide any clear recommendation about what time horizon should be adopted in comparisons of greenhouse gas emissions using GWP (Global Warming Potential) factors. Under the Kyoto Protocol, however, a hundred-year perspective is adopted.

In addition, it can be stated that a time perspective of a hundred years covers the inertia of the oceans and their influence on global average temperatures. Furthermore, carbon cycle models show that a hundred-year perspective represents a timescale over which a significant proportion of carbon dioxide emissions have left the atmosphere. This therefore indicates that a long time perspective is needed when comparing various fuel systems. This also means that, even if the instantaneous impact from the harvest residues scenario is similar to the natural gas scenario during the first 15–20 years, this has little importance in the long run. The Figure also shows that there is a significant difference between biomass fuels and fossil fuels, namely that the impact on the radiation balance from fossil fuels increases continuously while that from the biofuel scenarios reaches a stable level.

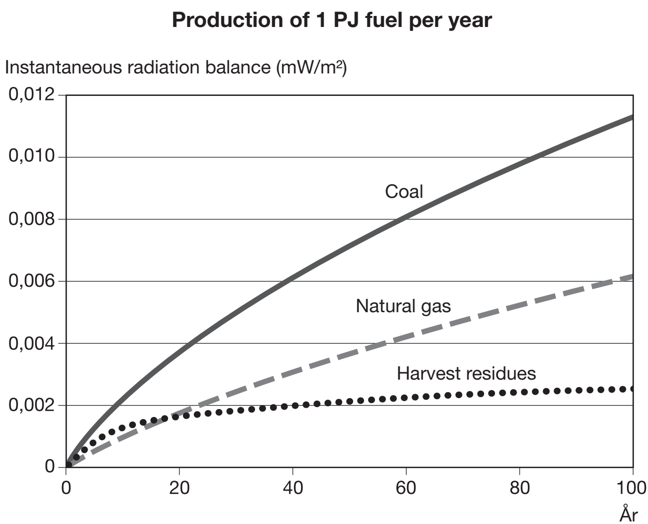


Figure 2. Instantaneous impact on the radiation balance from fuel chains in which 1 PJ (petajoule = 10^{15} joule) of fuel is produced and used each year.

Continuous carbon circulation

The fact that the fuel production systems are sustained is very important because it ensures a continuous production potential and continuous circulation of carbon between growing biomass and the atmosphere which means that atmospheric levels of carbon dioxide do not rise. This also means that replanting and sustained forestry are very important issues.

Ever greater demand for both biomass fuels and biomass for other use means that new and more intensive production systems may be developed. We consider it very important to take account of not only emissions of greenhouse gases but also other environmental influences when designing and devising requirements for these production and usage chains.

The Figures in this chapter have been taken from the report "Biofuels and climate neutrality", which was published by Elforsk in 2007. This report provides further information on biomass fuels and aspects of their climate neutrality. The views expressed in the report are those of the authors and not necessarily Elforsk's.

Kristina Holmgren is a civil engineer in Environmental and water technology and works in the climate department of IVL Swedish Environmental Research Institute Ltd. Over the last few years, she has been engaged on issues concerning the climatic impact of fuels from the lifecycle *perspective, which has included not only biomass fuels but also peat and fossil fuels. She also works with issues concerning control instruments and the costs of action relating to the climate and the energy sector.*

Mats Olsson is Professor of Forest Soil Science at the Swedish University of Agricultural Sciences. He conducts research and teaches on issues concerning the characteristics and use of forest land. In recent years, the focus has been on how forestry can contribute to reduced emissions of greenhouse gases by producing biomass that can replace other products, and by handling the soil in such a way that emissions from it decrease as much as possible.

Climate benefits of building with wood

Are there any climate benefits from making buildings with wooden frames instead of concrete frames? Yes there are, according to Leif Gustavsson, who reports the results of comparative analyses of concrete and wooden buildings. Wood-framed buildings produce lower levels of carbon dioxide emissions. To exploit the climate benefits fully, it is important that the biomass by-products from the wood product chain are used as fuel to replace fossil fuels.

Leif Gustavsson, Department of Technology, Physics and Mathematics, Mid Sweden University

Photo: Jens Blixth

Large-scale urban fires which raged in Sweden in the nineteenth century prompted a ban on the construction of wooden buildings comprising more than two stories. This ban remained in place until 1994, when Swedish construction standards were revised to require that buildings meet functional requirements. It then became possible to build wooden buildings with more than two storeys. However, the construction systems for producing such wooden buildings had not developed during the previous century, as they had with other construction systems, and multi-storey wood construction therefore did not gather pace with changes in the law. In North America, on the other hand, almost all three- and four-storey buildings are constructed with wooden frames.

A number of major projects are currently being conducted to develop wood construction in Sweden, including in Falun, Skellefteå and Växjö. There seems to be great potential for the development of wooden construction systems for multiple-unit residential dwellings in Sweden. An interesting question is whether there may be climate benefits from building in wood. Is less energy used in producing a wooden building compared with a concrete building? Are the net emissions of carbon dioxide lower? These are complex issues which are subject to various uncertainties, and relatively little research has been conducted in this area.

Wooden buildings compared with concrete buildings

This Chapter discusses whether net emissions of carbon dioxide differ if we produce a wooden building compared with a concrete building. We base this assessment on studies conducted on one of the first wooden multi-unit dwellings erected after the Swedish construction standards were amended in 1994. The multi-unit dwelling in question was built in Växjö as part of the Välludden project. The building comprises four storeys with a total of sixteen apartments and a total living area of 1190 square meters. An identical building with a concrete frame has been designed and costed. The two buildings provide the same residential service, and use the same amount of energy during the usage phase. The difference between the buildings lies in the use of different frame materials and in the ensuing consequential changes, for example in terms of sound insulation.

The fact that a building is built using a specific frame material does not mean that the building contains only this material. A wood-framed building also contains concrete, for example in the foundations, while a concrete-framed building may contain wood in, for example, the walls, roof, floors and doors. The aim is consequently not to build completely in wood or concrete, but to prioritize wood in the case of a wooden building and to prioritize concrete in the case of a concrete building. Table 1 shows the quantities of various materials incorporated in the concrete building and the wooden building in Välludden. We have assumed that both buildings have a service life of one hundred years.

Table 1. Materials incorporated in concrete and wooden buildings (tonnes of air-dried material).

Material	Wooden frame	Concrete frame
Wood	59	33
Particleboard	18	17
Plywood	21	20
Concrete	223	1 350
Lightweight aggregate concrete	4	4
Mortar	24	23
Plasterboard	89	25
Steel	16	25
Copper/zinc	0.6	0.6
Insulation	21	10
Macadam/gravel	315	315
Glass	4	4
Paper	2	2
Plastic	2	2
Sealing compounds	4	4
Paint	1	1
Ceramic tiles	1	1
Porcelain	0.6	0.6
Appliances	3	3

Wood produces less carbon dioxide for four reasons

Where wood-based products are used instead of concrete, net emissions of carbon dioxide decrease for four reasons: 1) the manufacture of wooden products generally requires less energy than the manufacture of concrete, 2) by-products of the wood product chain can replace fossil fuels, 3) carbon is stored in the wood material, which functions as a carbon sink, and 4) cement-making leads to carbon dioxide process emissions. When comparing concrete and wooden buildings, it is therefore important to bear in mind:

- how the use of energy differs for producing the buildings, including manufacture of materials and products incorporated
- the quantities of by-products from forest operations, wood processing, and from demolition of the building which are available for replacing fossil fuels
- the quantity of carbon stored in wooden products
- emissions of carbon dioxide from the manufacture of cement, and rebinding of carbon dioxide during concrete weathering

From natural resource to a finished building

To construct a building, a number of different materials are needed, which are listed in Table 1. A number of material systems are needed to produce these materials, which begin with extraction of natural resources and end with finished materials in the building. To calculate carbon dioxide balances, entire material chains need to be taken into account, including the transport incorporated. To cover the entire life cycle of a building, the demolition phase and the handling of the demolition material must also be considered.

Figure 1 shows a schematic flow diagram for wood – from forest to construction material and then demolition wood. To calculate the quantity of stemwood from the forest that is used to produce the wood products in a building, information is needed about the efficiency with which the stemwood can be harvested and converted to wooden products such as planks and boards, and what waste occurs on the building site and during transportation. With information on the quantity of stemwood needed, it is possible to calculate the quan-

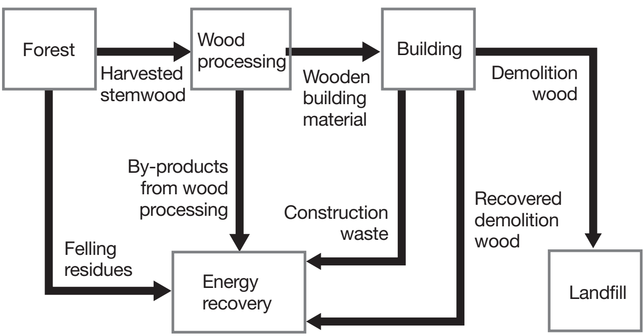


Figure 1. Schematic flow of wood material over a building's lifecycle.

tity of biomass in bark, branches, tops, stumps and roots and thus the flow of biomass and the organic carbon flows. The energy consumed in forestry, transport and processing of the biomass can then be calculated.

In the case of sustainable forestry with a rotation period of a hundred years, the forest will have regrown when the building is demolished after a hundred years. This means that the quantity of forest biomass harvested to produce wooden products for the building will have been re-established, so that the living quantity of biomass is as great as when the home was erected. This means that the carbon stores in living biomass do not change over the building's lifecycle. The carbon is stored temporarily in the building itself. When the building is demolished, it no longer stores carbon.

Less energy to produce a wooden building

The use of primary energy to produce the concrete and wooden building in Välludden is shown in Figure 2. Data on final energy use to produce the building materials is based on a Norwegian study. Primary energy use has then been calculated by taking account of losses in the energy supply system, such as conversion and distribution losses. This means that the entire energy system is considered, from natural resource to generated electricity, heat and transport fuel, including extraction, transport, distribution and processing of fuels.

It is apparent from Figure 2 that a considerably lower level of primary energy is used in producing materials for a wooden building than a concrete building. However, the consumption of biomass is greater for the wooden building. Energy use on the building site to construct a concrete or wooden building is of roughly the same magnitude and is not included in the Figure.

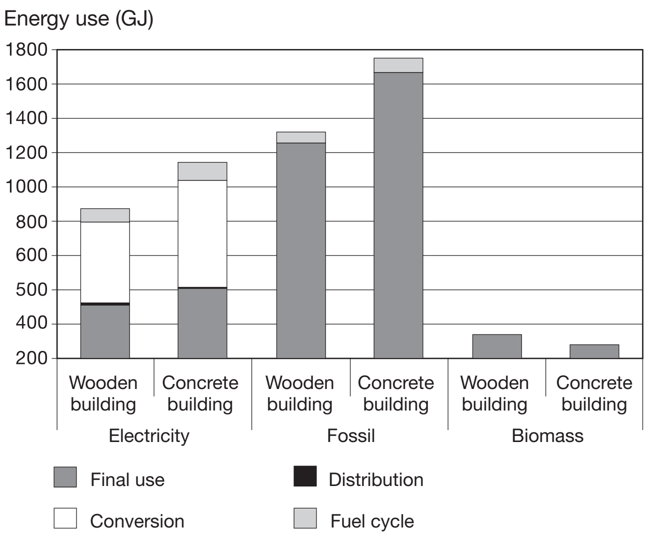


Figure 2. Primary energy use in gigajoules (GJ) to produce and transport materials for the concrete and wooden building.

With current energy standards for buildings, energy use in the user phase outweighs energy use for producing a building. In a future with more energy-efficient buildings, energy use to produce the buildings will increase in relative importance. Energy use during the user phase of the buildings and associated carbon dioxide emissions are roughly the same for the concrete building and the wooden building in Vällludden. The difference has been estimated at less than one percent.

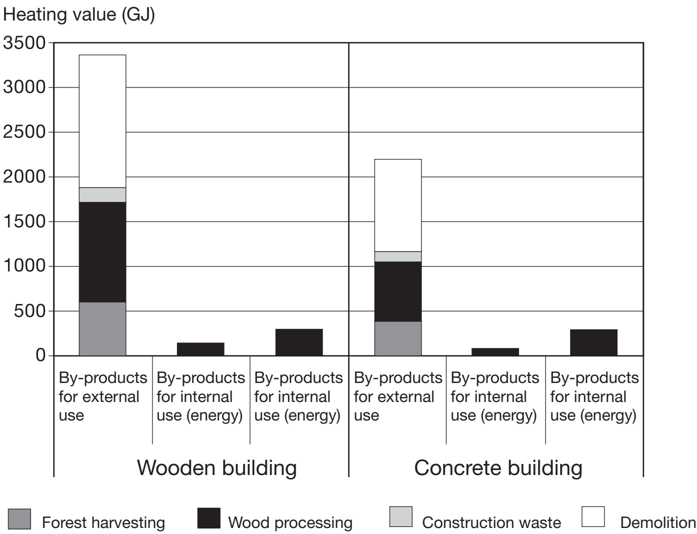


Figure 3. The quantities of wood-based by-products from forest felling, wood processing industries, building site waste and from the demolition of buildings – in gigajoules (GJ) after deducting the energy used to recover and transport the by-products.

More by-products with wood construction

The quantity of by-products from forest felling, wood processing industries, building site waste and from the demolition of buildings is extensive, and such by-products can be used to replace fossil fuels. Figure 3 shows the net energy in these by-products, after energy use to recover and transport them has been taken into account. By way of comparison, the amount of bio-energy used internally to produce the wooden products and the amount of raw material needed to manufacture the particleboard used in the buildings are also presented. The Figure shows that substantially more by-products are available when building in wood than when building in concrete.

Less carbon dioxide emissions to produce wooden buildings than concrete buildings

The difference in net emissions of carbon dioxide between producing a concrete building and a wooden building, calculated over their life span, is shown in Figure 4. The bars show how much higher carbon dioxide emissions are from producing the concrete building than from producing the wooden building. The lower emissions for the wooden building are due to the fact that lower levels of fossil fuels are consumed in producing the wooden building, that more fossil fuels can be replaced with wood-based by-products, that lower levels of cement are needed, which reduces carbon dioxide emissions from cement production, and that temporary carbon storage is higher for the wooden building. When concrete weathers, some carbon dioxide is re-absorbed via carbonation, which has been taken into account in the calculation. Two different scenarios for coal and natural gas as reference fuel are set out in the Figure.

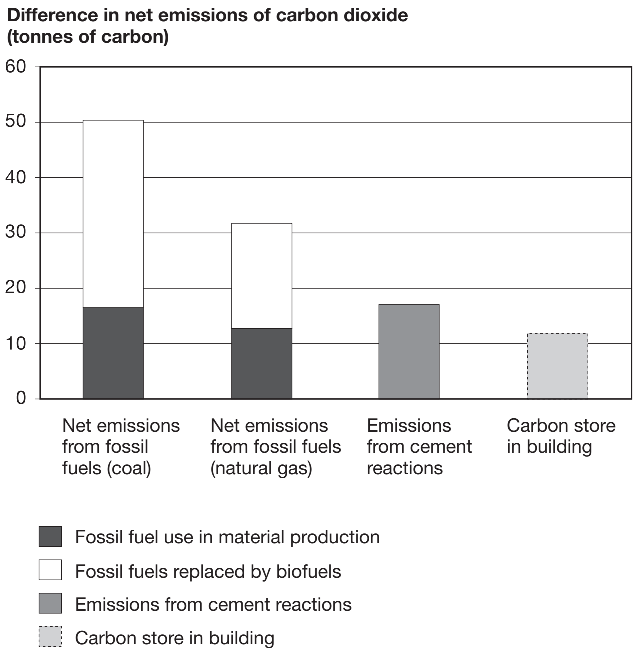


Figure 4. The bars show how much higher the net emissions of carbon dioxide are from producing the concrete building compared with the wooden building. The Figure shows carbon dioxide emissions from fossil fuels in which either coal or natural gas is used to generate electricity to produce the building material (dark grey), where biomass by-products replace either coal or natural gas (white), from cement making with due regard for carbon dioxide uptake in connection with concrete weathering (medium grey), and temporary carbon storage in building material (light grey).

The Figure shows the importance of using wood-based by-products to replace fossil fuels (the white part of the two bars on the left). Over the lifecycle of a wooden building, net emissions of carbon dioxide may be negative owing to the fact that more emissions from fossil fuels can be avoided by using wood by-products than are released in producing the wooden building. If the by-products are not used, the wooden building loses some of its climatic advantage compared with the concrete building.

Carbon storage in a building has only temporary importance. The temporary carbon store in a building's wood material is of no significance for net carbon dioxide emissions over the building's lifecycle. However, if the total number of wooden buildings increases, carbon storage in buildings will increase so long as more wood is incorporated in new buildings than is released by the demolition of existing buildings.

Climate benefits with wooden buildings

Do net emissions of carbon dioxide generally fall if we build wooden buildings instead of concrete buildings? Figure 4 shows the climate benefits of building in wood for a multi-unit residential dwelling. However, the exact quantity of material in a building varies according to how the building is designed and what construction solutions are chosen. Primary energy use for producing the materials depends upon the way in which the materials are produced. Nevertheless, uncertainty analyses show that, within a broad spectrum of variation, wooden buildings display lower net emissions of carbon dioxide than concrete buildings. Parameters that have been varied include, for example, how efficiently the cement is produced, how efficiently the timber is dried, the type of cement and aggregate, the level of reuse of steel, transport distances, what proportion of wood-based by-products is used to replace fossil fuels and what type of fossil fuel is replaced. A number of international studies also show climate advantages of building wooden buildings.

The construction cost for the wooden building in Välludden has been calculated to be lower than for the concrete building. This means that the construction of wooden buildings can lead to reduced emissions of carbon dioxide without economic disadvantages. The lower emissions of carbon dioxide and the reduced use of primary energy for wooden buildings also means that economic policy instruments that tax carbon dioxide emissions and/or energy use increase the competitiveness of wooden buildings. Using forests to build wooden buildings also yields a high added value.

Leif Gustavsson is Professor of Ecotechnology at Mid Sweden University. He conducts research on energy and material systems and in particular on how bio-based systems can be designed and implemented to efficiently reduce greenhouse gas emissions and the use of fossil fuels.

Energy systems of the future – the importance of choosing the right regulatory instrument

It is likely that biomass will assume great significance for the transition to a more sustainable global energy system and also form an important part of such a system. It is less likely, however, that bioenergy is the universal savior it is sometimes portrayed as being in Sweden. With the right choice of technology-neutral instrument, we have the opportunity of leaving the doors open for better future technology and an effective bio-energy system, writes Åsa Löfgren.

Åsa Löfgren, Department of Economics and Statistics, University of Gothenburg

In June 2006, the Swedish Prime Minister's Commission to combat oil dependence submitted its final report. Within the report, the Commission suggests that Sweden reduce its oil dependence sharply by, in combination with initiatives to boost energy efficiency, mainly investing in biomass fuels to replace fossil fuels in industry, the electricity and heating sectors and in the transport sector. In recent years, storms, flooding, drought and global average temperatures have significantly contributed to global climate change currently occupying a clear place on the political agenda.

Many environmental problems arise from the lack of well-defined ownership rights. Many of our resources, such as clean air, lakes and seas, have traditionally not had clear owners. In the case of climate change, this means that anyone can release carbon dioxide without having to cater for the adverse effects this has on global climate. Authorities (nationally and internationally) nevertheless have many ways of influencing enterprises and citizens to cut emissions to the level considered appropriate.

Optimal emission levels are usually referred to in economics. This term denotes the levels of emissions at which the cost of the emission is equal to the positive effect that it has. Although it might initially appear that there are no positive aspects to emissions, we all want food, clothing and a number of other consumption goods, and their production gives rise to some form of emission. The big question is what level of emissions we can conceive of, which depends partly on the effects of the emission (is it a very dangerous substance or an emission with limited effects?), and what production technology is available.

Various instruments

A first difficult question is therefore to decide what level of emissions we are willing to accept. It must then be considered what scope there is for "guiding" enterprises and individuals so that they do not release more than this. It will probably be concluded that there are many ways of achieving a certain level of emissions. But are there ways that are better than others? The commonest tools, known as instruments, that authorities have for influencing enterprises and individuals are economic instruments, rules and information. Other forms of instrument are nevertheless available, such as investment contributions.

With economic instruments, a price can be placed on emissions, for example in the form of a carbon dioxide tax. When emissions are assigned a price, enterprises and individuals consider the cost when making their production and consumption choices. This often means that emissions fall as a result of, for example, efficiency-boosting initiatives, cleaning and fuel changes. In simple terms: when the price of a good increases, one is unwilling or unable to buy as much. Typical economic instruments are taxes, emissions trading and subsidies.

Depending on the situation, different instruments vary in quality. They have different effects on, for example, costs for companies, willingness to invest and attitudes, and also function with varying effectiveness in situations of uncertainty. There are often major uncertainties, both in terms of enterprises' treatment costs and what environmental damage emissions may have. Before choosing instruments and suitable emission levels, an analysis of the costs and benefits of the emissions (cost/benefit analysis) and the advantages and disadvantages of various instruments should be conducted.

Impossible ambition

Sometimes, however, it is not politically possible to achieve the emission levels considered suitable. To a large extent, this applies to climate change. Most researchers agree that drastic cuts in carbon dioxide emissions (50–90 percent) must be achieved to stabilize the climate, but in reality it is very difficult to get countries to co-operate to reduce emissions if this has an adverse effect on, for example, economic growth.

Sweden has in many ways been a leading country in cutting environmentally dangerous emissions, even if a great deal more can be done. Greater understanding of the effects of carbon dioxide emissions and Sweden's supply of forest has, over the past decade, very much helped drive its ambition to cut the use of fossil fuels by increasing the use of bioenergy. The aim of increasing the share of biomass fuels in the Swedish energy system is not only to cut carbon dioxide emissions. It is also a question of energy security and reducing oil dependence in combination with utilizing the nation's natural resource of forests.

The instruments that currently have an effect on the use of biomass fuel are principally carbon dioxide tax, emissions trading and green electricity certificates as well as the investment programs known as Lip (Local investment program) and Klimp (Local climate investment program).

Environmental taxes

Taxes on oil were introduced back in the 1970s, and prompted a switch from oil to, in particular, coal, biomass and electricity. In 1991, a carbon dioxide tax was introduced which corresponded to SEK 0.25 per kilogram of carbon dioxide, together with taxes on sulfur. At the same time, the energy tax decreased by 50 percent. (The aim of the energy tax is chiefly to generate tax revenue while the carbon dioxide tax has an environmentally controlling motive.) This was part of a green tax change in which the aim was to cut income tax funded by higher environmental taxes.

Concern about competition conditions for Swedish production has prompted exemptions and reductions in the carbon dioxide and energy tax. Protecting one's own production is not uncommon in Europe; for example, Norway, Denmark and Switzerland have implemented cuts in carbon dioxide tax for industry. In 1993, Swedish industry was fully exempted from energy tax, and the carbon dioxide tax was lowered. The carbon dioxide tax was then revised upwards several times. Owing to the introduction of emissions trading, the carbon dioxide tax has fallen for the trading sector (see below). In its budget proposals for 2005, the Swedish Government expressed the aim of phasing out the carbon dioxide tax for the trading sector in the long run.

How, then, does the carbon dioxide tax affect bioenergy use? As the carbon dioxide tax is applied to the price of fossil fuels, it becomes more interesting to use biomass fuels instead of oil and natural gas. In relative terms, biomass fuels become less expensive than fossil fuels. Growing demand will contribute to increased prices of biomass fuels and greater competition for raw biomaterial, and thus greater use. Even if the aim of the carbon dioxide tax is not to reward biomass (primarily, it must encourage reduced emissions of fossil carbon dioxide emissions), this becomes the case in Sweden, where we have plenty of access to forests. A great advantage of the carbon dioxide tax is that it is technology-neutral. By putting a price on carbon dioxide, willingness is created within enterprises to develop more energy-efficient technology and hopefully investigate completely new technology.

Carbon dioxide sequestration is an exciting and relatively new technology of this kind which is under development. This technology makes it possible to separate carbon dioxide emissions from, for example, a coal-fired power plant and emissions can then be stored deep in the ground (special sedimentary layer), which means that the coal-fired power plant would not contribute to climate change. This kind of technology is very important particularly as many countries have access to cheap coal (e.g. China), which means that coal-fired power plants will in many countries be built for a long time to come. Carbon dioxide sequestration must, however, be regarded as a transitional technology (in the long run) as it is not possible to store any amount of carbon dioxide in the ground. For about a hundred years, the technology could, however, be crucial in stabilizing our climate.

The carbon dioxide tax therefore controls things *from* the fossil fuel usage stage, but what arises instead is up to the enterprise to choose. Enterprises probably have a better understanding of technology potential than authorities, and the technology neutrality of an instrument is therefore regarded as something positive.

Electricity certificates

Electricity certificates have contributed to the generation of electricity from biomass having increased in recent years, as the certificates have set a minimum limit for renewable energy. Electricity producers receive an electricity certificate (thus a form of subsidy) for every megawatt-hour of renewable electricity produced. The electricity certificates are sold to electricity consumers who are obliged to purchase a certain quota of renewable electricity. The idea behind the certificates is that they should promote renewable energy sources and not specifically bioenergy, i.e. the electricity certificates are technology-neutral so long as renewable energy is involved.

As a result of the first years' design of the electricity certificate system, which had a relatively short lifetime, electricity production from biomass was what was promoted by the trading in certificates. As it was uncertain whether the system would last beyond 2010, this led to discrimination against investment in new plant and new technology that was entirely dependent on the electricity certificate system to be profitable, for example wind power. This was particularly unfortunate as the thinking behind the system was to encourage new technology. Under new rules, however, the certificate system will remain in place until 2030, which will therefore benefit a number of technical solutions that generate renewable electricity.

Emissions trading

Emissions trading was introduced in January 2005 under the EU Emissions Trading Scheme. This trading scheme encompasses the energy sector, production and processing of metals, the mineral industry and the paper and pulp industry. These sectors are known by the generic name of the trading sector. In terms of promoting bioenergy, emissions trading works in a similar way to the carbon dioxide tax. Emissions trading places a price on carbon dioxide and therefore disincentivizes the use of fossil fuels. The great difference compared with the carbon dioxide tax is that emissions trading also functions as a regulatory mechanism by placing a ceiling on carbon dioxide emissions. Unlike the carbon dioxide tax, emissions trading also covers electricity production.

Emissions trading was the subject of regular debate within the Swedish media in autumn 2006 and spring 2007. The system has been heavily criticized for being unworkable, and there are of course both disadvantages and advantages to such a system. It would take a separate chapter to elucidate this fairly. What can be said, however, is that the emissions ceiling was set in 2005 and we therefore knew back in 2005 what the levels of emissions would be over the period 2005–2007. It is therefore nothing new that emissions are high compared with what would be needed to stabilize the climate. The intention behind the first period is, however, that it should be a trial period, and the most important thing is that the system is in place and that all involved are given time to learn how it works. This indicates that emissions trading is an administratively complex system that costs enterprises and authorities a great deal of time and resources.

The Lip and Klimp investment programs

For many environmental problems to be solvable, it is of the utmost importance that enterprises invest in available cleaner technology and also have the courage to invest in new technology. Trust that new technology must solve environmental problems is especially clear in the case of climate change. As mentioned, one of the advantages of economic instruments is that they foster willingness (incentives) within enterprises to invest in cleaner technology. The degree of such willingness depends upon, among other things, the price of carbon dioxide; in the case of low prices, willingness is less than where carbon dioxide taxes are high.

For enterprises to have the courage to invest in uncertain new technology, complementary instruments are therefore needed, e.g. taxes or emissions trading. Examples of such instruments may include research or investment support such as the local investment program (LIP), which was introduced in 1998 and which went on until 2002, when it was replaced by the climate investment program (Klimp). The two investment programs differed slightly in format, but one of the aims was to promote the use of renewable raw materials (energy conversion to renewable energy). The investment programs entailed the State partly funding investments made by local authorities, enterprises and other players. The programs have cut carbon dioxide emissions. It is also likely that they have contributed to investments that have promoted the use of bioenergy, even if the total effect on biomass fuel within the energy system is still uncertain as Klimp is still running.

The future – what do we actually want?

Recent discussions have dealt with whether liquid biofuels should be the object of greater investment in the transport sector. Over a transitional period up to and including 2020, it may be important to replace petrol with raw biomaterial, i.e. phasing-in of biofuel in the transport sector. However, it is doubtful whether it is a good idea to invest too many resources in "first-generation liquid biofuels" (liquid biofuels from Swedish agricultural crops such as grain ethanol). On the other hand, it may be important to invest in second-generation liquid biofuels such as DME and methanol (produced via gasification).

Strict future climate undertakings – to cut carbon dioxide emissions radically – in which the price of fossil fuels in the transport sector also rises globally could increase demand for bioenergy and create scope for global trading in biomass fuels, with various levels of refinement. This would probably not be sufficient to create a high level of use of biofuels in the transport sector, but further instruments will be required, such as fuel certificates, which ought to function in roughly the same way as current electricity certificates.

It is currently more important than ever to consider the technology neutrality of instruments. By using fuel certificates or directly rewarding vehicle biofuels in some other way, technology of the future within the transport sector is also controlled. If we want more energy-efficient technology and new technology such as hydrogen vehicles to be possible in future, it is important to retain technology neutrality.

There are a number of other arguments for and against greater use of bioenergy in the global energy system which are unfortunately outside the remit of this Chapter. It is likely that bioenergy will assume great importance for the transition to a more sustainable global energy system and also form an important part of such a system, but it is less likely that bioenergy is the universal savior it is sometimes portrayed as being in Sweden. With the right choice of instrument, we also have the possibility of leaving the doors open for, if possible, better future technology and an effective bioenergy system.

Åsa Löfgren is a Doctor of Economics at Göteborg University and holds a post-doctorate position funded by Mistra's climate program (Clipore). She has studied various aspects of economic instruments and is currently focusing on what determines enterprises' environmental investments and what role instruments play in these. She recently completed a report on the future biofuel market.

Political skill necessary for new industry to establish

If the EU targets for renewable energy use are to be achieved, the rules must be designed so that they actually support the growth of industries. The plans call for investments of the order of 1000 billion Euro in bioenergy alone. To achieve such investments, policy instruments that introduce new uncertainties should be avoided, writes Tomas Kåberger. Based on experiments in various European countries, conclusions can now be drawn on the performance of various instruments.

Tomas Kåberger, International Institute for Industrial Environmental Economics, Lund University.

The transition from fossil fuels to renewable energy is not limited by a shortage of physical resources. Nor do we lack technology for utilizing bioenergy. With the current prices of fossil fuels it is also profitable to increase the use of renewable energy. With political incentives, significant profitability and large increases are possible. However, development is still slow in relation to the EU's aims, and global demand for energy and the challenge of preventing expensive climate change may require even faster development. Those in control of the financial resources to build a sustainable energy system are still hesitant. Their hesitation can be explained and the reasons made void. If this is done with political skill, development may pick up speed.

For many years, there has been broad support for increasing the use of renewable energy. The use of fossil fuels has led to emissions of acidifying, health-impairing substances and climate change. In addition, physical resources are depleted as the planet's reserves are burned. Similarly, there are social costs for nuclear power in the form of routine emissions of radioactive substances and problems concerning the spread of capabilities for manufacturing nuclear weapons. The latter problem would be significantly worse if an effort to restart nuclear expansion were to succeed.

In some nuclear countries there are significant direct subsidies and public liabilities for nuclear waste management and decontamination.

The problems with the predominant energy systems are important but not the only reasons to increase the use of renewable energy. In the following, some previously tried policy instruments are presented: environmental taxes, subsidies, electricity certificates and carbon dioxide emissions trading.

Environmental taxes provide a sound basis for investment decisions

Economic theory developed back in the 1920s explained how environmentally harmful emissions are a cost that is disregarded by natural markets. As a result, emissions become economically excessive resulting in economic losses to society. It was also shown that such emissions can be limited to an appropriate level by environmental taxes so that whoever manages the emissions takes account of the damage that the emissions cause to other people. Environmental taxes as a method for limiting environmental disruptive emissions have then received further support from public finance theory, identifying environmental taxes as an optimal funding of public spending. With the lack of international control over an international market, this facility has been rarely used. However, it is used in Sweden, particularly in sectors not exposed to international competition.

Environmental taxes result in the less environmentally harmful alternatives becoming profitable to use. Entrepreneurs who develop the new alternatives are not affected by administrative costs caused by the instrument itself, but need only worry about meeting customers' desires. Environmental taxes also appear stable as they have rarely been reduced. Enterprises thus base their investment decisions on environmental taxes. They dare make investments for which payback periods of 5–10 years are stipulated. In their calculations, environmental taxes have played a decisive role.

Grants as investment in less expensive technology

There is another kind of argument in favour of increased use of new technology for sustainable energy supply. Bioenergy technology, wind power technology and solar energy technologies hold the prospect of becoming much less expensive to use than they are currently. Potential is greatest for solar electricity and greater for wind power than for bioenergy conversion, but exists for all three.

By initially subsidizing industrial activity, costs can be gradually lowered as experience and industrial production on a large scale are built. This may lead to energy solutions that are less expensive than conventional energy supply technologies. The subsidy thus becomes a social investment that is paid back as a result of everyone then receiving less expensive energy. This justifies subsidies for new technology in the form of investment grants or in the form of initially higher, but gradually reduced price premiums for production from facilities using the new technologies.

Political incompetence

Even when political decision-makers have stated that it is their goal to support new energy industries, their decisions have destroyed the industries they set out to support. Swedish support to the solar heating industry is an example of how support systems counteract industrial development. In the 1980s and 1990s, investment support was introduced several times for installation of solar panels for hot water production. Solar water heating was popular. Demand grew fast. Entrepreneurs formed companies, invested in equipment, hired and trained staff. Soon, the popular solar energy had sold to the extent that the budget was depleted and no more subsidies could be paid. Demand fell. And as politicians immediately started talking about re-introducing the subsidy, demand fell to zero. Even those who would profit from building a solar water heating system without a subsidy waited. It would be even more profitable with the subsidy.

Companies with interests and staff to pay found themselves in a difficult situation. Within a few months, before the subsidy was re-introduced, many filed for bankruptcy. The next time few would try to build companies again.

A devastating stop-and-go system of this kind was demonstrated by the Swedish Parliament for a couple of years against the will of the supported biomass burner industry. A healthy, growing industry went from sales of 12,000 burners on a growing market to selling 21,000 burners in the same, but subsidised, period the following year. After hiring staff and increasing capacity they found themselves with a financially unviable overcapacity when sales dropped to 4,000 burners the following year.

New market risks with new instruments

In recent years, a number of instruments have been introduced that combine planned-economy targets with market-economy means. Examples are the European system for carbon dioxide emissions trading and the national systems for mandatory quota-based electricity certificates. The economic theory underlying the systems is that once political decisions have set fixed targets for emission cuts or an increase in electricity production, emissions trading or production quotas are a way of achieving the targets at the lowest cost. When it is a matter of optimizing the operation of existing facilities, this is relevant in reality too. From an investor's perspective, the systems have other important features. In practice the theoretical efficiency cannot be achieved. The same applies to those considering investing in technical development and building enterprises. Uncertainty about future prices in an inflexible market when investing in facilities is important because of the risk of the investments becoming so unprofitable that investors lose all their money.

A market risk is also introduced by systems for quota trading. As with emission trading, this is greater than the price risk for most ordinary goods because demand is determined on a planned-economy basis and the price falls to zero if oversupply arises and may end up being very high in the event of shortage. This high price risk means that investors must compensate for the high risk with requirements for expected high profit levels before decisions are taken. Prices for consumers thus end up being higher than they would have been if the value of emission cuts or new production had been predictable.

For those considering building up an industrial operation, the systems' negative feedback is also a major deterrent factor. If success is achieved in selling, for example, solar cells on a large scale, the planned target is exceeded – and the production quotas then become worthless! If a technology to cut carbon dioxide emissions for coal-fired power stations on a large scale is developed successfully, emissions will remain within the planned target and the quotas will immediately become worthless!

Even if these systems have been launched with good theoretical arguments and planned-economy targets that are reasonable from the energy policy perspective, they do not contribute to the industrial development which were the actual aim.

Political uncertainty

All rules of the game may be changed. For anyone considering investing, the political risk of economic conditions being changed is an important factor. Issues regarding whether a subsidy system will continue after the next national budget has taken effect or after the next election and are crucial for anyone considering investing in facilities for generating electricity or heat, which normally have a payback period of some 10–15 years.

When nuclear power was to be supported, the long-term perspective of the Nuclear Liability Act's provisions was important. Suppliers of components for nuclear power stations required assurance that they would never be held financially responsible for faulty components causing an accident costing billions of dollars or pounds. The reactor owner's needed to know that their liability was strictly limited so that owners and financiers would never need to bear financial liability for major accidents. In this context, legislation enacted by a parliament was not deemed sufficient. Only once the elected parliament's legislation had been cemented into international conventions which would take many years to change, were the support systems considered sufficiently reliable for private investments in nuclear power stations.

The Swedish system of electricity certificates and mandatory quotas is a system that has been perceived as marred by political uncertainty. Firstly, the parties that formed the political majority which decided on the system were not entirely in agreement internally. In addition, representatives of the opposition asserted that the system should be abolished. The system had a direct effect in that existing facilities made use of the possibility of producing more electricity with biomass. However, it was difficult to get banks and investors to believe that electricity certificates would have a significant value in long-term investment calculations. It was even more difficult to get anyone to start building up an industry to supply power stations in Sweden.

Political power held by established industry

For players who develop new energy technology, the established energy groups not only represent competitors on the market. Whereas new enterprises have little economic capacity for anything other than their own production and are poorly organized, the major energy groups have substantial capacity for influencing energy policy decision-making. This heightens the political risk for entrepreneurs launching renewable energy operations.

The political power held by established industry is clearly apparent within the EU. The small and inadequately resourced Commission is an easy victim for pressure, particularly if the players also have the close links with national governments that power companies often have – although electricity is their main trade. One example is when these power companies managed to get the EU to introduce the system of trading in emissions rights so that these rights were assigned free of charge to those who had previously released high levels of emissions. In addition, those building new facilities using fossil fuels were also to be granted emission rights free of charge. For companies with coal-fired power stations, this meant a huge financial gain. The electricity price was raised to the level at which coal-fired power stations could have purchased the emission rights and still been profitable. But the rights had been obtained free of charge, and so this merely meant increased profits of the order of 100 billion Euro in the first trading period for the owners!

As new coal-fired power stations also obtain emission rights free of charge, whereas biomass-fired power stations do not, the system does not provide any incentive to invest in carbon dioxide-free electricity production.

The entire system is sufficiently complicated for only a few responsible politicians and a negligible proportion of citizens in Europe to understand what huge sums of money have in this way been transferred from electricity consumers to owners of coal-fired power stations in Europe. For many players considering investing in the industrialization of technology for renewable energy, however, this was a clear sign that their potential competitors had political power that could be expensive to challenge.

Market power held by established industry

Over the last decade, electricity companies in Europe have bought each other up as much as they have been allowed to by the competition authorities. The reason for them buying each other up is that they see it as more profitable to be bigger than to continue being smaller. This also means that it is difficult for new enterprises to enter the market and grow in competition with the established major enterprises. Established ones can, via their control of the market, in practice therefore shut out new technical solutions – if they do not themselves choose to adopt them. It is generally difficult to prove that enterprises deliberately have used their size to control pricing to harm certain competitors. The mere risk is nevertheless a factor that prevents investors from entering the market.

At the interface between market power and political power are all the standards and conventions that regulate what is required for energy products to have access to the markets. Standards for vehicle fuels have long hampered the blending of bio-based fuels into standard petrol and diesel fuels. Rules and procedures concerning access to the electricity supply network have similarly been used to create barriers to impede new electricity producers and new energy technologies.

Solutions

Market economic theory provides a sound basis for devising rules that solve society's energy problems in an economically efficient way. It is important to realize that efficiency concerns a modernization of the energy industry in which completely new technologies are to be industrialized. The result will be a system in which renewable energy sources will provide energy at a lower cost than energy from current systems. The instrument must therefore be aimed at creating conditions for investment and for industrial development. This is something quite different from minimizing costs in the short term to achieve a planned-economy target.

Politicians and authorities must not believe that the enterprises that have been built around current unsustainable energy technology will propose rules that lead to development, or that these enterprises will pioneer new technologies. A well-resourced bureaucracy with integrity is needed to ensure that established industry is unable to manipulate the system, creating barriers to impede new technologies.

Lessons

Experience from experiments with instruments shows that environmental taxes work and have led to rapid development for bioenergy in the sectors in Sweden in which they have applied. In the electricity sector, in which environmental taxes have not been tried, industrialization has worked best in countries that have had foreseeable prices or price premiums for renewable electricity production, e.g. Germany. The hybrids of planned-economy and constructed markets have in practice proved less successful in developing new industry.

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