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A SUSTAINABLE ENERGY SWEDEN

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Content

Glossary

Deposit. Non-renewable resource, e.g. fossil fuels and minerals.

Energy. Motion, or ability of motion, e.g. the disordered motions of the hot molecules in a cup of coffee. [J, joule]

Exergetics. Theory of exergy and its applications.

Exergy. Work, i.e. ordered motion, or ability of work, e.g. the motion of a falling object. [J, joule]

Exergy Analysis. Calculation of the total input and output of exergy of a product or service.

Exergy Destruction. Exergy that vanishes in an irreversible process, also named irreversibility.

Fund. A physical resource maintained by a natural resource flow, e.g. hydropower, agricultural crops and harvested forest.

Irreversible. Real processes are always irreversible, i.e. exergy is destroyed, in order to occur. This is a condition of existence of time

Life Cycle Analysis or Assessment. Method to calculate the environmental impact of a product or service, from ”the cradle to the grave”.

Life Cycle Exergy Analysis. Method to calculate the environmental impact of a product or service in terms of exergy and with respect to use of non-renewable resources.

Natural Resource. A physical resource with natural origin.

Natural Resource Flow. A physical resource flow originating from natural processes, e.g. sunlight, wind and ocean currents.

Physical Resource. Energy, Matter and Information, as carrier of exergy.

Reserve. The known and profitable part of a resource.

Resource. Potential exergy asset.

Summary

This article exemplifies the possibilities to meet the need for sustainable development with regard to the life support systems. The object of study is a well developed country with a high dependence on non renewable resources and a high level of per capita use of energy, in particular for space heating. It should also be noticed that this country has by far highest per capita use of nuclear power in the world, or about 29 GJ/yr capita.

The energy supply in Sweden as in most other countries are mainly based on fossil fuels, e.g. coal, fuel oil and gas, and nuclear fuel. These resources are deposits, which are depletable and bring harmful substances to the environment, see Wall, The Life Support Systems and Sustainable Development. From an exergy diagram of use of physical resources in Sweden 1994 it is obvious that the system is not sustainable, see Figure 1. From this point of view the so called developed countries in the world are actually underdeveloped.

This diagram originates from a description of the total use of exergy resources in the Swedish society, see Figure 3 of Wall, The Use of Natural Resources in Society. From this we learn that the only sustainable inputs to the present resource base are in PJ per year: solar about 20, hydro about 248, and most of harvested forest about 424 and agricultural crops about 300. However, we must raise big question marks for the present resource use in forestry and agriculture that is mainly based on the use of non renewable resources as fossil fuels and minerals. The inflows of deposits, i.e. ores, nuclear and chemical fuels are doubtless not sustainable.

In order to meet these problems a sustainable energy supply system must be developed, which is based on renewable resources. These resources are either natural flows such as solar and wind energy or flows from funds such as hydro and biomass.

This article presents the possible use of renewable resources for Sweden. These are solar, wind, wave, saline and thermal gradients in the sea, sea currents, tide, geothermal, biomass, hydro and peat. The access, the technology, environmental effects and the economy for the most promising systems for Sweden is treated.

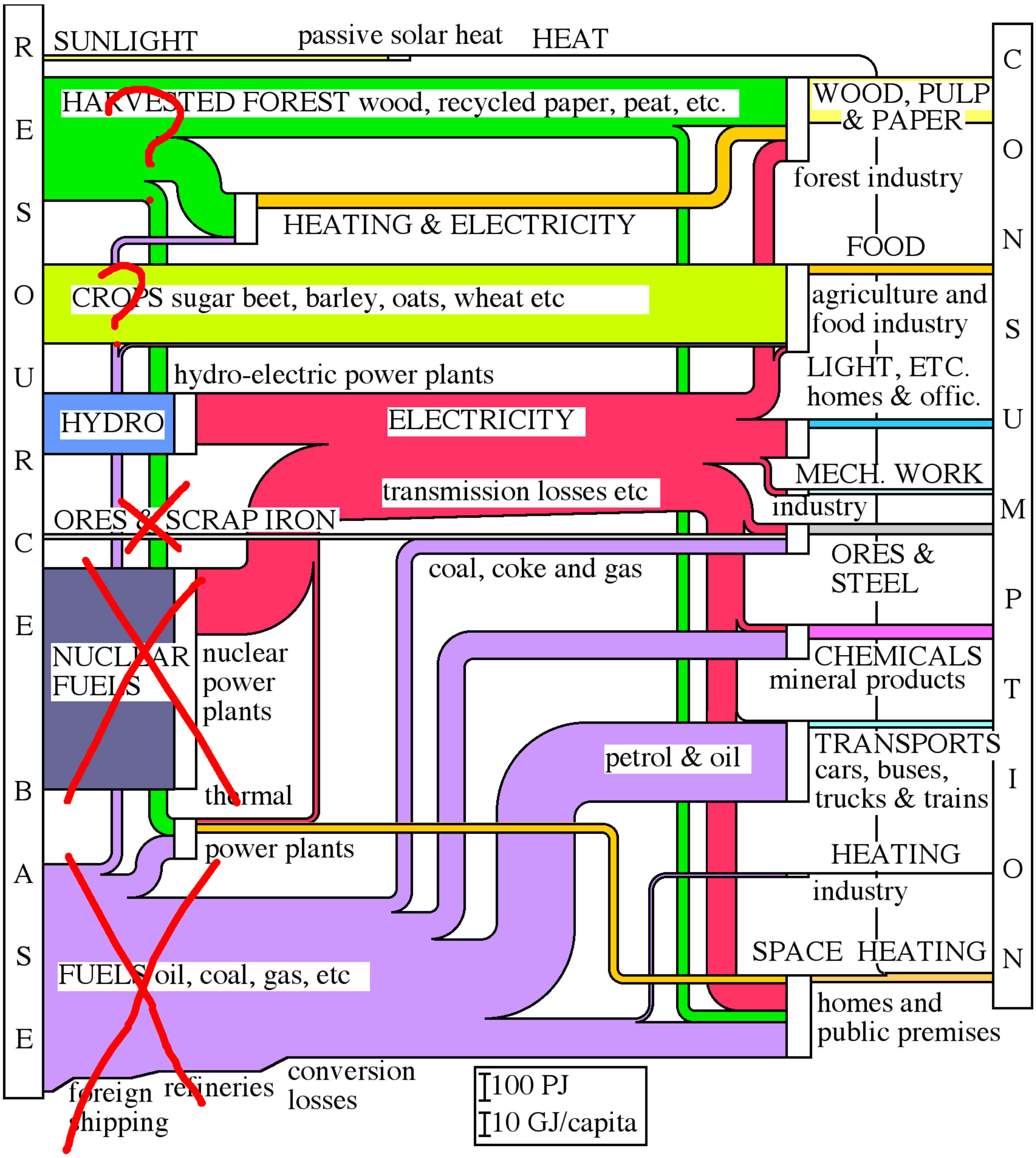

Figure 1. The exergy conversion system in the Swedish society in 1994 were the non sustainable resources are marked with red. Total input about 2720 PJ of which about 900 PJ are sustainable.

Physical resources are carrier of exergy and when they are used in the society it is the exergy that is being consumed. The exergy of an energy or material substance gives the minimal work that is needed to create that substance from ambient conditions. When a substance is refined, e.g. a metal, the exergy is increased by being added from other substances. An increase of exergy in one part always implies a even larger destruction elsewhere so that the total exergy always decreases. Thus, in order to optimize the use of physical resources these are measured in exergy. A high exergy efficiency indicates an efficient use of resources and minor emissions to the environment. The exergy concept is presented in detail in a separate article, see Wall, Exergetics.

Solar

From the article Wall, The Life Support Systems and Sustainable Development, we know that the surface of the earth receives about 1000 W/m^2 perpendicular to the radiation at clear sky.

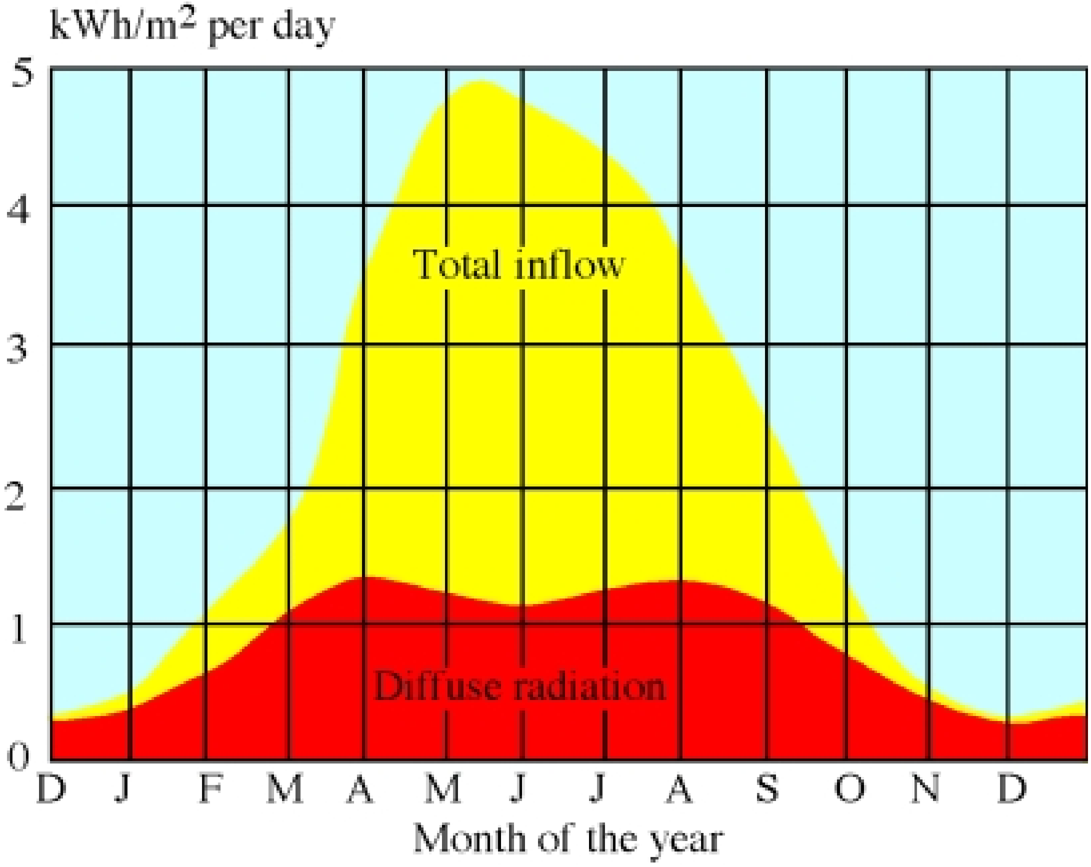

Figure 2. The average inflow of total and diffuse solar radiation on a horizontal surface in Stockholm.

Due to refraction and transmission of the radiation in the atmosphere it is divided into parallel and diffuse radiation, or direct and indirect light. The amount of diffuse radiation increases with the amount of steam, aerosols and other particles in the air. In Sweden the amount of diffuse radiation is about 50 percent of the total radiation during one year. In the summer the share of diffuse radiation is only about 20 percent whereas in winter it is about 80 percent, see Figure 2.

In Stockholm a vertical surface towards south receives more radiation per square meter then a horizontal surface. The optimal angle with the ground is about 60 degrees. This angle should decrease with the distance to the equator.

In areas like the Sahara and Arizona the solar radiation may reach 3400 kWh/m^2yr on a horizontal surface. The surface of Sweden receives about 360 000 TWh/yr or 1 300 000 PJ/yr of sunlight. The inflow towards a horizontal surface varies from 800 kWh/m^2yr in the north to about 1000 kWh/m^2yr in the south, see Figure 4.

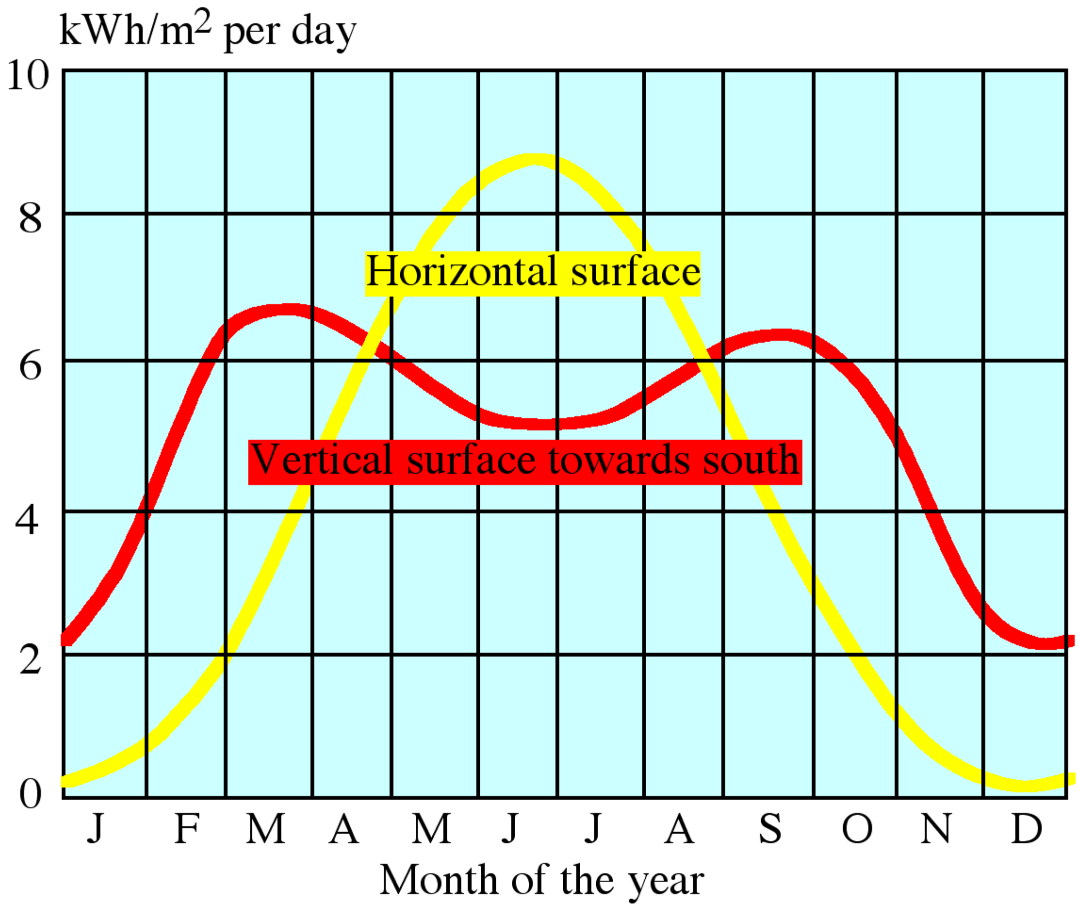

Figure 3. The solar radiation in Stockholm at clear sky.

Presently there are a number of profitable and technically well operating systems to convert solar radiation into useful heat, electricity, mechanical work etc.

Most profitable are systems of direct conversion of sunlight into heat for heating of water and for space heating. Already today in Sweden the sun contributes to the heating needs in the winter season. A well designed house, with large areas and windows facing the sun, may cover up to 10 percent of the heating needs by solar. Well insulated houses with automatic heat regulation, so called "intelligent" buildings that are equipped with solar panels and a heating storage system may well manage without external input of heat. Other attractive options are the ability of generating electricity and fuel, e.g. hydrogen for use in an automobile.

To generate high temperature heat, to be used in industrial processes, by direct conversion the radiation must be concentrated. In Sweden with a high percentage of diffuse radiation this kind of applications are of less importance. Direct conversion into mechanical energy is possible, however, in such cases it is probably more efficient to first generate electricity by photo voltaic systems. In most cases the use of solar also requires a system for storage or back up. If electricity is generated it may be transmitted to the national electrical grid that will act as a storage system. In Sweden where this is dominated by hydropower, it has an excellent capacity to work together with solar and wind based systems. Hydropower can easily adjust to rapid changes of excess or of shortage of electricity in the grid. From this regard the present Swedish electrical system offers excellent conditions for the introduction of renewable energy resources.

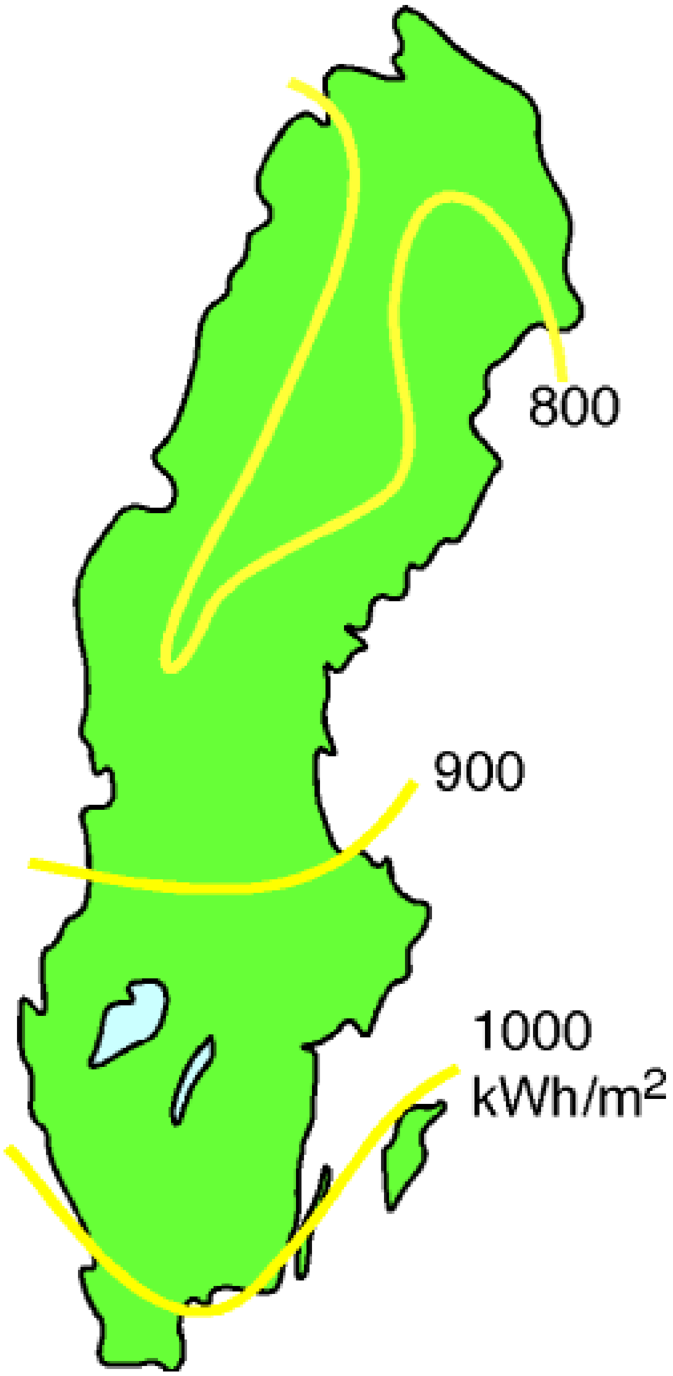

Figure 4. The total inflow of solar radiation per year in Sweden.

For heating purposes it is convenient to distinguish between passive and active systems. Passive systems makes use of the solar radiation without specific equipment. A careful design, i.e. orientation of the building with respect to the sun and local topography, suitable type, size and arrangement of windows, good insulation, ventilation and heat regulation, can reduce the need for space heating to less than 50 percent of that of a normal house. An active system involves the use of solar collectors together with a storage system. The combination of a passive and an active system may well meet the total need of light, heat and comfort of a carefully designed building. The total inflow of solar radiation towards a typical house in Sweden amounts to about 100 times the need of exergy for space heating, see Appendix 1. Thus, in the future houses will not only produce their own need for heat and electricity but also be the main supplier of the energy system.

Solar collectors

A solar panel usually converts solar radiation into hot water or air. Principally, it is a heat exchanger where the outside is, preferably, a selective surface and the inside is circulated by water or air. A selective coating absorbs solar radiation well and has low emission of heat. The purpose of the glass layer is the same as in a green house, i.e. to allow the solar radiation to go through and to keep the heat inside. Circulating water or air goes through pipes or channels in order to capture the heat. To produce useful heat the temperature of the "black" surface becomes much higher than the environment, which makes heat losses into a problem. By good insulation this is solved for the backside and sides. The heat losses from the front is often reduced by an extra layer of Teflon film that also improves the selective effect. However, this will also reduce the net inflow of solar radiation, particularly at oblique angles. Losses from conduction and convection can be reduced by vacuum inside the solar panel.

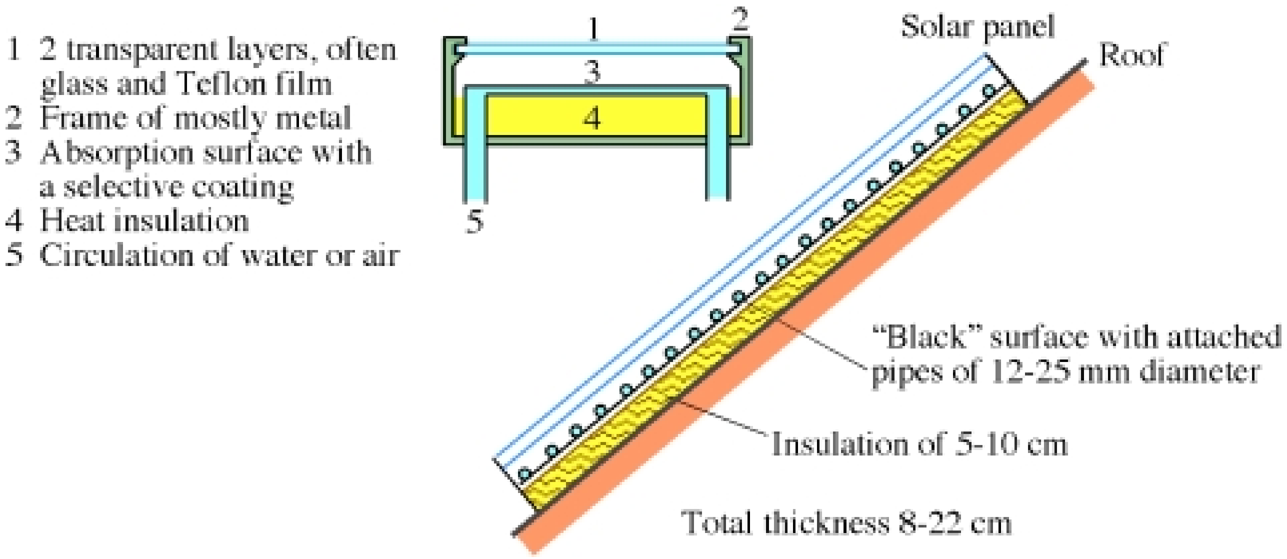

Figure 5. A typical solar panel to put on the roof. To the left is a principal cross-section, and to the right a cross-section of the mounted panel.

The optimal angle with the horizontal plane should be the local latitude plus 10 degrees, which for Sweden becomes about 70 degrees. The reduction of the efficiency if a vertical orientation is selected is usually negligible. Exact orientation towards south is either not necessary, a deviation of up to 25 degrees only gives a minor loss of heat.

The transmission losses through the glass is about 15 to 20 percent and about 65 to 80 percent of the incoming solar energy may be converted into hot water or air. Due to low temperatures of about 40 to 60 degrees the exergy efficiency becomes only about 2 to 3 percent. A complete system with heat storage may reach about 40 percent energy efficiency or about 2 percent exergy efficiency. The poor exergy efficiency should be compared with present systems that have less than 5 percent exergy efficiency, or sometimes even less than 0.025 percent, see Figure 4 in Wall, The Use of Natural Resources in Society.

A self circulating system is obtained by placing the water tank above the solar panel. The solar heated water will rice in the pipes to the top of the tank, whereas the colder water will fall down to the bottom of the solar panel and thereby close the circuit. If the tank is placed below the solar panel a circulation pump is needed. A water system offers a high heat capacity and a simple heating system. The drawbacks are danger of freezing and problems with corrosion.

A system with air as heating media has no danger of freezing. Rocks may be used for storage. However, a fan is needed, it becomes bulky, the rock storage is about 3 times bigger than a water tank, and the transfer between air and solid matter is poor.

By combining the solar panel with a heat pump its working temperature can be lowered. This will reduce the heat losses and increase the amount of captured solar energy, particularly when it is cloudy. With a heat pump the storage can be charged at a much higher temperature than the panel permits. The same heat pump can also be used to deliver heat at a much higher temperature than the storage permits, thus making better use of the storage. Heat pumps may also be used to extract the solar heat stored as geothermal heat in the upper ground layers. With suitable heat pumps, e.g. absorption heat pumps, solar panels my also be useful for industrial processes, e.g. heating, drying, cooling and freezing.

The agriculture uses a lot of electrical energy in fans to dry grain and hay. This is in the summer, which makes solar panels suitable. Solar heated air will considerably reduce the time needed and consequently reduce the use of electricity.

Solar heating systems for houses is mainly a seasonal storage problem, see Figure 6. About 40 percent of the yearly use must be stored. This is preferably done jointly in large volumes, since the capacity increase with volume whereas the heat losses only increase with area. With suitable ground conditions, as rock or soil with minor heat leakage, this is done underground with hardly any visible signs.

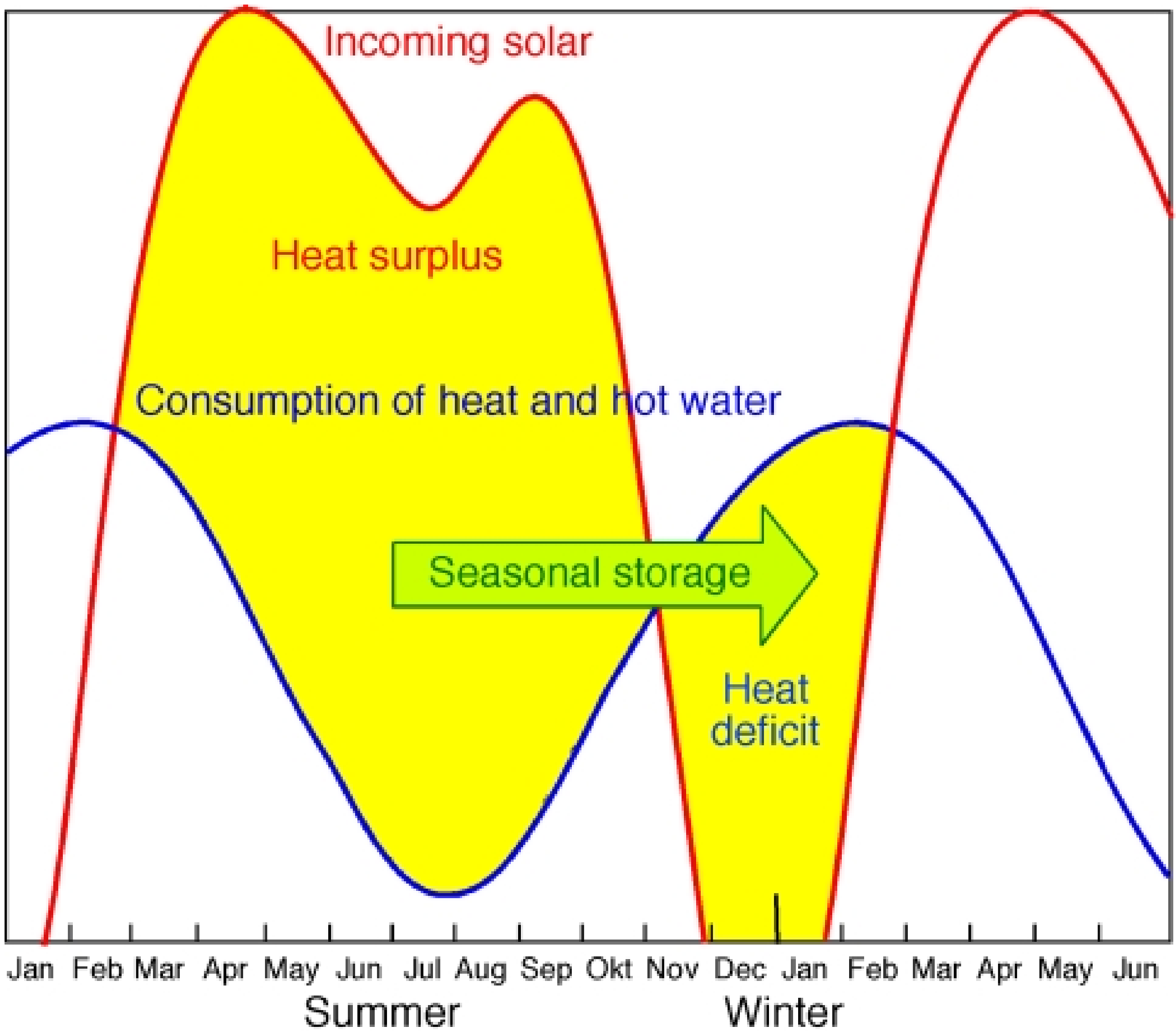

Figure 6. A typical energy balance of a solar heated house with seasonal storage. The red curve is the incoming solar and the blue curve is the need for heat.

Solar cells, or photo voltaic cells, convert light, i.e. both direct and indirect sunlight, into direct-current electricity in a solid-state semiconductor device. The basic principle is illustrated in Figure 7. Incoming sunlight "pushes" electrons into the p-layer and leaves holes in the n-layer. This will generate an electric power to be extracted through an electric circuit. The solar exergy is converted into electrical exergy. The exergy factor of solar energy is 0.93, i.e. 100 W solar energy can ideally convert to 93 W electricity. However, for commercial systems this becomes only about 10 W. However, solar cells are declining in cost, improving in efficiency, and increasing rapidly in sales, and soon they will compete with conventional power systems.

Solar cells could be combined with solar panels to extract both electricity and heat. This will probably be commercialized soon. Concentration of sunlight is also a possible technique to reach high temperatures and to improve the efficiency.

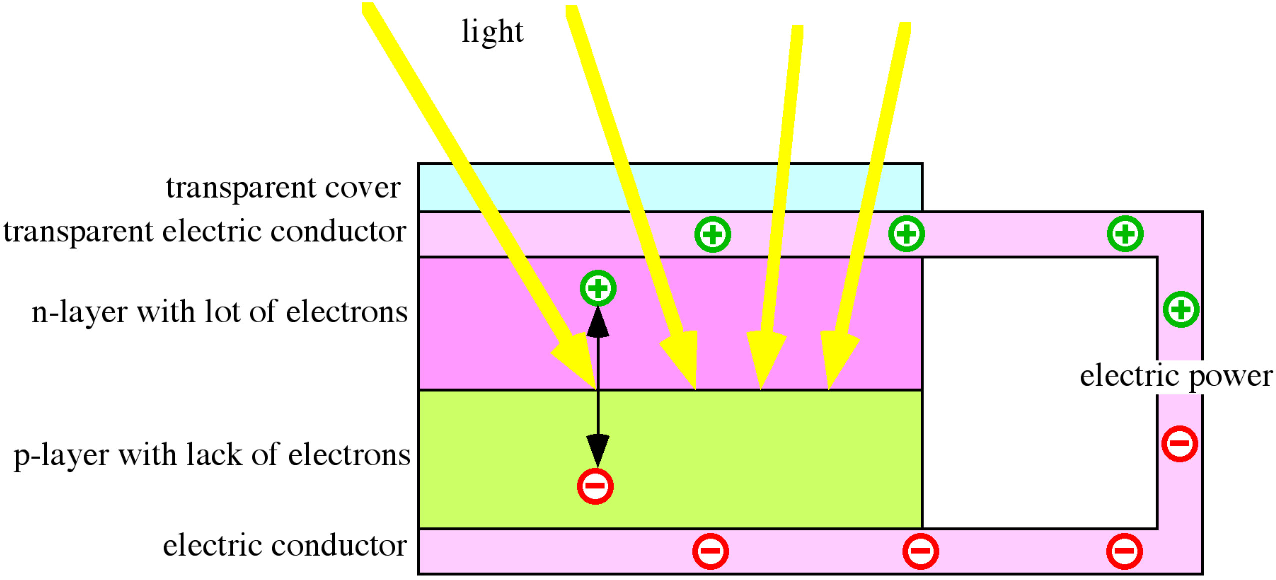

Figure 7. Basic principal of a typical solar cell, i.e. a solid state semiconductor photo voltaic cell. Light is both direct and indirect sunlight.

The environmental impact from solar collectors is negligible as long as all used material is recycled properly.

It is also of importance to consider the exergy pay back time, i.e. to perform a Life Cycle Exergy Analysis (LCEA), see Wall, Exergetics. For poorly designed solar panels this may well exceed the expected life time. However, for most solar collectors with material recycling the exergy pay back time is less than a year. Sometimes solar panels also replace other roofing material, thus saving exergy.

If the use of heat and electricity in Sweden is solely based on solar systems with 10 percent efficiency this would need about 1.6 percent of the land area, a 83 km square or about 770 m^2 per capita. Most probable, this will make roofs and walls facing south important energy suppliers in the future.

Biomass

Biomass is organic material produced by photosynthesis in plants. The chlorophyll is an active substance in the production of carbohydrates and oxygen from carbon dioxide, water and light. Solar exergy is transformed into chemical exergy in the plants, i.e. biomass. The theoretical efficiency of the photosynthesis is about 15 percent. However, due to limiting factors etc. the real efficiency is often below 1 percent. If we regard all plants on the earth about 0.1 percent of the solar exergy is converted into biomass.

About 0.1 percent of the inflowing solar exergy is naturally stored in plants, with an exergy content of about 18 GJ/kg of dry substance or 8 GJ/m^3. Swedish timber cutting is about 53 m^3 or 520 PJ see Table 1 in Wall, The Use of Natural Resources in Society. The exergy content of the outputs consisting of wood, pulp, and paper, was about 174 PJ. The rest was mainly used for energy purposes in the pulp and paper production or as firewood. A part of what is left in forest may be ecologically and economically extractable, about 80 PJ.

To make biomass an alternative it must be produced separately, from quickly growing species as sallow, poplar and alder. A high production of biomass will require heavy inputs of fertilizers and irrigation. Suitable land for this is limited to closed farmland, swamp, land next to water in the south and along the seashore in the north. However, this will conflict with other interests as agriculture, forestry and recreation. Clear-felled area could be used for two generations of brushwood before being reforested to even improve forestry. The brushwood will probably improve the productivity of the soil and reduce the vermin. By using half of the clear-felled areas this would annually produce about 90 PJ together with about 10 PJ from the power line areas. Reeds produced in nutritious lakes in the south could give about 10 PJ per year, however, it may conflict with bird life.

The agriculture produce about 160 PJ of crops, see Table 2 in Wall, The Use of Natural Resources in Society, and in addition about 140 PJ of residues etc. of which 30 PJ is brought back into cultivation. Straw and manure accounts for about 90 PJ each that by fermentation could produce about 70 PJ of methane in total. However, all this residues are not available for energy use.

The forest industry produces waste of about 160 PJ that is mostly being used for energy purposes. The food industry offers about 4 PJ from waste of which, however, only 1 PJ may be extractable as fuel. Waste from households are presently used, about 20 PJ, however most of this should rather be recycled.

Biomass, as firewood and straw my be combusted in power plants for production of district heat and power, i.e. electricity. Biomass can also be converted into fuels with different qualities. Biomass with no lignin as manure is preferably digested into methane that may also give a good fertilizer. A farm with more than 25 cattle could become self-sufficient with heat and fuel for machines. The combustion of methane gives more or less only carbon dioxide and water. Fuel cells are promising future converters. Biomass with lignin can be converted into charcoal, methanol and hydrogen by pyrolysis. Methanol can be added up to 15 percent to gasoline with no change to the engine. Wood can also be grained to powder to be used in specially designed diesel engines. A fuel is more valuable the less oxygen it contains, thus, carbon, hydrogen and hydrocarbons are excellent fuels, see Table 1.

Table 1. Exergy content of some biomass products.

Product	Exergy kWh/kg	Exergy MJ/kg
Straw, dry matter	4.5	16
Straw, 90% dry matter	4.1	15
Wood, dry matter	5.0-5.6	18-20
Wood, 85% dry matter	4.1	15
Wood, 60% dry matter	2.7	10
Wood, 50% dry matter	1.7	6
Methanol	5.4-6.1	19-22
Methane	14	50
Hydrogen	33*	120

*Liquid hydrogen has about one forth of the exergy per liter value of fuel oil.

The exergy of biomass such as wood, brushwood, straw and waste may be processed into more convenient forms by pyrolysis, catalytic reduction, digestion etc. In pyrolysis the material is heated with no access to oxygen that makes most of the hydrocarbons convert into new forms. The cellulose will convert into gases of hydrogen and methane and liquids that contains methanol to be used for fuels. The left solids may also be used as a fuel. However, the exergy spent in the process must be considered. In catalytic reduction the biomass is mixed with carbon monoxide at 300 bar and 350-400 degrees Celsius to produce a liquid fuel. The exergy is about 30 GJ/kg and with about 0.1-0.3 percent of sulfur. Digestion or fermentation with no air is a biochemical process and is suitable for biomass with low content of cellulose such as manure, sewage and green plants. About 50 percent of the exergy will remain in the produced methane. Digestion also produces a suitable fertilizer to be recycled. A process diagram is illustrated in Figure 8, where environmentally risky processes are indicated by red boxes.

The environmental consequences of an increased output from the forest are complicated and needs further research. A complete use of trees including branches, needles, stumps and roots would increase the output by 30 to 40 percent. However, this would also imply more mechanical damage to the ground and removal of nutrients that may be replaced by fertilizers with unknown effects. More input will generate more output, and a Life Cycle Exergy Analysis, see Wall, Exergetics, will give the answer to if the process is sustainable or not.

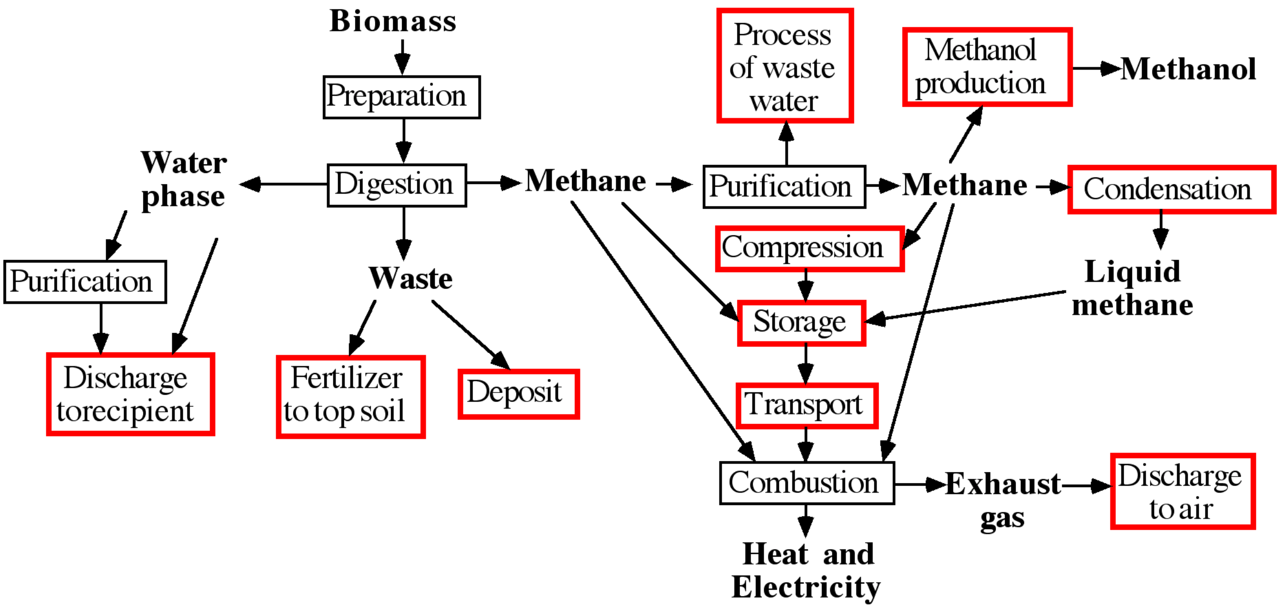

Figure 8. Digestion of biomass into methane, methanol, heat and electricity. Red boxes are environmentally risky processes.

Wind

The exergy power of the wind increases strongly with the speed. If the speed is doubled the exergy power is increased by eight times, see Table 2. The theoretically extractable part is limited to about 59 percent. Thus, areas with high stable average wind speeds are most suitable, i.e. areas close to the sea and offshore.

Table 2. Exergy power at different wind speeds.

Speed, m/s	Power W/m^2	Extractable power W/m^2
5	80	47
11.5	1000	590
20	5200	3100

Local fluctuations in the wind speed would be effectively eliminated by a large number of wind power plants geographically well distributed. Available wind exergy in the winter season is about twice that in the summer, which well correspond to the exergy need. Available wind exergy also increases with height, at 100 meter the exergy may be 3 to 6 times what it is at 10 meter. The total wind exergy over Sweden amounts to about 1 TW or 36 000 PJ per year. From areas with an average wind speed of over 7 m/s more than 100 PJ could be extracted with care taken to recreation, historical sites and settlements. Areas of 6-7 m/s average wind would add over 300 PJ. Thus, in total about 400 PJ annually could be extracted from about 13 000 wind mills with 100 m rotor diameters on 100 m towers. A typical design of a 2 MW wind power plant with 72 m rotor diameter on a 68 m tower is depicted in Figure 9. This makes wind power the most promising immediate alternative. 1995-98 wind power generation increased by more than 4 times in Sweden, and at the end of 1999 the installed capacity was 216 MW from 480 turbines. In addition, Sweden offers exceptionally good conditions due to the large amount of hydro power to match variations in wind power. Also excess of wind power can be stored by pumping water uphill.

Figure 9. A 2 MW turbine with a 72 m rotor diameter on a 68 m tower. [www.windpower.dk]

The environmental impact, noise and risks of wind power is only local and can be satisfactory met. Also, they will disappear with the plant. The exergy payback period for modern wind turbines is about 3 months, and it is truly sustainable with regard to a Life Cycle Exergy Analysis.

Hydro

Falling water carries a lot of exergy. A water flow of 500 m^3/s falling 100 m may generate about 500 MW of electricity. The total potential in Sweden is about 700 PJ of which about 50 percent may be economically possible to extract. Today, with regard to other interests about 220 PJ is extracted, see Wall, The Use of Natural Resources in Society. Beside adding smaller hydro power plants further increase of hydro power is to be expected. The environmental impact is mostly local, however, severe and more or less permanent.

Osmosis

The difference in concentration of salt when fresh water mix with sea water is a potential exergy resource equivalent to a water fall of about 250 m. However, probably it is impossible to realize due to the environmental conditions, since huge amount of water that carries a myriad of biological life forms has to pass through fin-meshed technical constructions. This exergy is today converted into heat that gives these areas a slightly milder climate.

Waves

When the wind exergy is converted into waves a new form of renewable exergy appears. A storm in the Nordic sea generate waves with 300-500 kW/m. A wind of 10 m/s may generate waves that carries about 20 kW/m in the Nordic sea, but along the Swedish coast this will become only 1-5 kW/m. With its long coast line Sweden has a potential of about 200 - 400 PJ per year, of which 40-100 may be extracted as electricity. There are a number of promising technical solutions, however, still not economical. The environmental impact is mainly local and will give a more calm seashore.

Ocean thermal

Ocean Thermal Energy Conversion (OTEC) is not regarded as a possible resource for Sweden.

Ocean currents

This is not regarded as a possible resource for Sweden.

Tidal

This is not regarded as a possible resource for Sweden.

Peat

Peat is produced in bogs and swamps were biomass is deposited due to lack of oxygen, which is a first step towards a fossil fuel. Thus, a carbon dioxide sink and an oxygen source. The yearly growth of peat in Sweden is equivalent to about 10 PJ. With regard to environmental conditions and alternative use this is not to be regarded as a renewable or sustainable resource.

Geothermal

Sweden does not offer suitable conditions for geothermal exergy except in few places in the south with porous sandstone. This will have no measurable effect to the Swedish system. It is to be recognized as a renewable resources, only the seasonally stored solar exergy in the ground, which may be extracted in suitable places by use of heat pumps, is a renewable resource.

Conclusions

An estimation of the total amount of renewable exergy resources that are available in Sweden can be done, see Table 3. These estimations relates to Swedish conditions, with environmental concern and technical limitations. Thus, the sustainable use of biomass, hydro and wave is limited from environmental concern, i.e. the precautionary principle. Also the sustainable use of osmosis, ocean thermal, ocean currents, tidal, peat and geothermal is regarded as negligible. The resource base of a sustainable Sweden is limited to mainly solar and wind as the main suppliers of exergy for the energy system. This can only be met by conservation and improved exergy efficiency. The intensity are estimations of the exergy flow per land area for the different forms. Hydro uses a large area for water dams, which gives a low intensity.

Table 3. Potential renewable exergy flows in PJ per year.

Exergy flow	Global	Sweden potential	Sweden sustainable	Intensity kWh/m^2yr
Solar	2 500 000 000	1 300 000	2000	200
Biomass	3 600 000	1 400	800	10
Wind	72 000 000	36 000	400	200
Hydro	72 000	700	200	70
Osmosis	72 000	350	-	-
Wave	1 400 000	350	60	500
Ocean thermal	?	?	-	-
Ocean currents	250 000	?	-	-
Tidal	100 000	?	-	-
Peat	700	10	-	50
Geothermal	700 000	10	-	500

Acknowledgment

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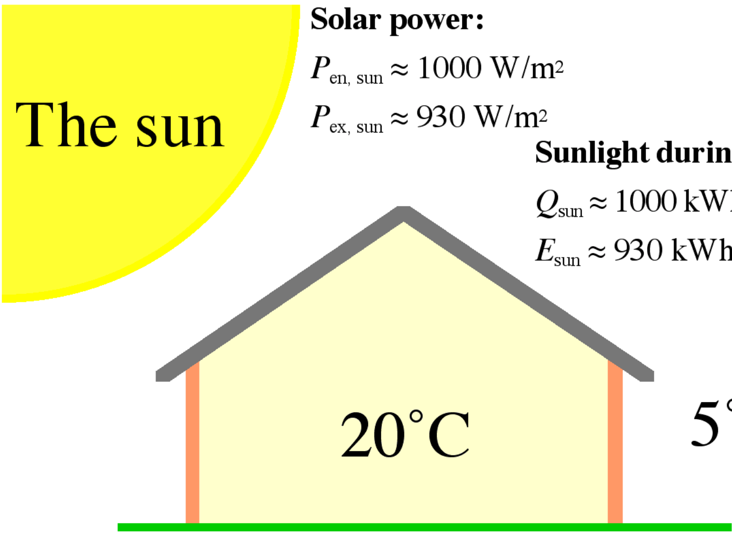
www.windpower.dk

Appendix

The conditions with regard to the availability of solar energy and exergy and need for energy and exergy for space heating is illustrated in Figure 10. As we see their is no lack of neither energy nor exergy for the heating of our buildings. Actually, in the future our buildings, i.e. the roof and walls facing the south, will be the main suppliers of exergy to our energy system. This is obvious from Figure 10.

Solar en(x)ergy versus heating (cooling) needs



Solar power:

$P_{en,\,sun} \approx 1000\ \mathrm{W/m^2}$

$P_{ex,\,sun} \approx 930\ \mathrm{W/m^2}$

Sunlight during one year:

$Q_{sun} \approx 1000\ \mathrm{kWh/m^2}$

$E_{sun} \approx 930\ \mathrm{kWh/m^2}$

Assume a one storey house of 100 m²

Available yearly sunlight for the house, assumed area 100 m²:

$$Q_{available\ sunlight} \approx 100{,}000\ \mathrm{kWh}$$

$$E_{available\ sunlight} \approx 93{,}000\ \mathrm{kWh}$$

Heating need during one year in Sweden

(without good insulation):

$$Q_{heating\ need} \approx 20{,}000\ \mathrm{kWh}$$

$$E_{\ heating\ need} \approx 0.05^{*} \times 20{,}000 = 1000\ \mathrm{kWh}$$

Relation between available and needed energy and exergy:

Available sunlight/heating need in **energy ≈ 5 times**

Available sunlight/heating need in **exergy ≈ 93 times!**

$$^{*}\frac{E}{Q}(20^\circ\mathrm{C}, 5^\circ\mathrm{C}) = \frac{20-5}{273+20} \approx \frac{15}{300} = 0.05$$

Figure 10. Solar inflow versus heating needs in terms of energy and exergy for a typical Swedish situation.