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R & D of Energy Technologies

Annex A
III-Renewable Energy

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AIII-1 Research and Development Needs in Photovoltaics

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We present here a description of the photovoltaic (PV) technology in view to determine the research needs for a cost effective mass utilisation of this technology. The paper contemplates different alternatives ranging from the present dominant silicon technology to the novel proposals towards a next generation of photovoltaic concepts.

AIII-1.1 Physical grounds

The photovoltaic effect allows for a silent and reliable conversion of the luminous power into electricity by means of the so called solar cells. They are made of a semiconductor with two energy bands separated by an energy gap. The basic principle of a solar cell is simple. Photons pump electrons from the lower band, called the valence band, to the upper band (the conduction band). Once there, selective contacts able to connect only (or mainly) with the conduction band can extract the electrons at a high (free) energy and render them, once they have utilised their additional (free) energy in some kind of useful work, to the valence band trough another selective contact of different type. This mechanism will (ideally) last forever as no waste, except that of the incoming photon, is produced in it. So when light shines, the electrical power can be supplied again.

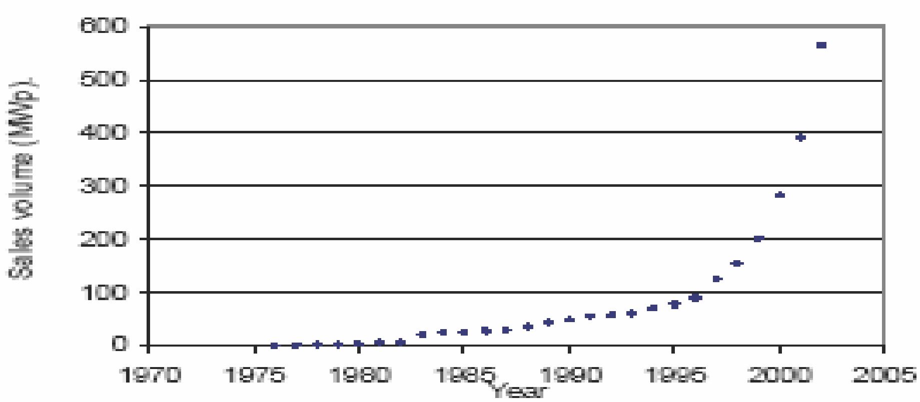

Figure 1. Annual sales of solar cells.

However, to do this, the delivery of the electrons for useful work has to compete with the natural tendency of the electrons to fall into the valence band where they have less energy. In semiconductors, chemically and structurally almost perfect (single crystals), the internal return to the valence band is hampered by the relative lack of particles to which the extra energy can be transferred. Ultimately such particles are photons emitted by the solar cell as luminescent radiation, and this is unavoidable as it is the detailed balance counterpart of the absorption. However, if the semiconductor is not perfect enough the energy can be easily delivered to vibrational states in the crystalline lattice (heat) and the electrons fall into the valence band without having produced useful work. The need of this highly perfect semiconductor to make the solar cells is one of the reasons for the relatively high cost of the present solar cells.

AIII-1.2 The PV industry

Despite this high cost, the industry of solar cells fabrication is experiencing nowadays a very fast growth. We present in Figure 1[1] the histogram of solar cells sales. Solar cells are rated in watts peak (Wp) : the maximum power that a solar cell can give at 25ºC under a solar power flux of 1000 $W\cdot m^{-2}$ (at the standard solar spectrum on the earth surface). The 2002 market has had an economic value of about €1.5 billion for the cell manufacturers (€4-5 billion for the users).

The annual market has grown slowly until 1996. After this date, the growth rate has become explosive. Many PV factories are doubling their production every two years. In 2002, 92.7% of this production corresponded to crystalline (mono 36.4%, multi 56.3%) silicon cells, 6.4% to thin film amorphous silicon cells, 0.9% to cadmium telluride or copper indium diselenide thin film solar cells[2]. Technologies, not based on silicon, are all experiencing a relative decrease in the market.

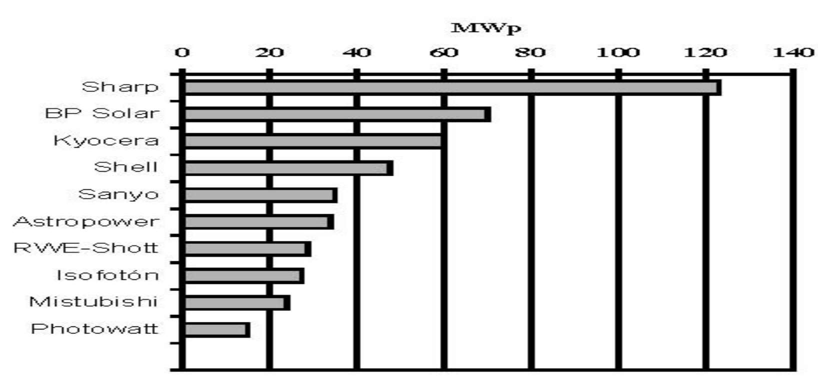

Figure 2. The top ten industrial actors in PV.

The main actors in this business[3]are represented in Figure 2. In 2002, they totalized 83% of the world sales. Japan is the first manufacturer followed by Europe and the USA. In Europe, Germany, Spain and France were the main manufacturers in 2002. (in 2001 the production in Spain was larger than in Germany)[4].

The most important and faster growing PV market is today grid connected houses[5]. In Japan and several European countries, they receive some kind of public subsidy, sometimes important, that adopts different modalities, depending on the country. Processes of PV modules are decreasing according to a learning curve[6] of 81%. This means that every time that the cumulated cells production doubles, the prices are reduced to 19%. This is not as good as in the memory business, but better, for instance, than in the wind energy.

We have developed[7] a prospective model that couples the learning curve and the demand elasticity to foresee the market and price evolution. After the present period of quick growth, the model foresees a period in which the growth will be limited by the availability of capital for a product that is more expensive that the prevalent electricity. If the industrialised countries are willing to expend every year up to 0.4% of their GDP in PV installations the cost of the PV electricity would reach the costs of the prevalent electricity by 2050. They will be reached later with less investment and earlier with more investment. We consider unlikely that the needed level of investment will be produced and therefore that PV, with its present technology, can constitute an alternative for mass production of electricity in the first half of the century, but we are not sure. However the invention and commercialisation of novel technologies with a better learning curve would be the quicker way towards mass production of PV electricity.

Besides the cost, the main drawback of PV electricity, is its intermittent nature, coupled to the sun availability. Some studies have determined that an electric network can deliver up to 30% of electricity[8] from intermittent sources (sun and wind). Naturally, these utilities must know well the statistical consumption pattern of their final users, and so organise the dispatching. They must learn to consider them as potential negative consumers, with different consumption patterns (including this negative consumption). Of course, any storage discovery can ease the storage needs of PV electricity but probably the cheapest storage is a sophisticated electric network management.

Any other alleged PV drawback we have heard of is not a real one. There are no problems of space (all the electricity for a home can be largely obtained in its roof space) nor of pollution (silicon cells manufacturing is not a specially dangerous industry, and once disposed, the silicon cells are far less poisonous than any ordinary electric equipment).However the fact is that it is necessary to wait 3-6 years (depending on where it is installed) to recover the energy spent in manufacturing a solar cell[9]. But solar cells last very long. Companies guarantee them for 20 years (actually the modules are probably lasting less that the cells themselves) and most probably they can operate for much longer. Novel technologies foresee a reduction of the energy recovery time to about 1 year.

To summarize it is perhaps interesting to bring here the words of Shell International, the oil company[10],

"Since 2025 when the first wave of renewables began to stagnate, biotechnology, materials advances and sophisticated electric network controls have enabled a new generation of renewable technologies to emerge By 2050 renewables reach a third of world primary energy and are supplying most incremental energy."

AIII-1.3 Crystalline silicon technology

Following our argumentation, the potential of the silicon cells to reach the prices of the prevalent electricity cannot be totally discarded. At least, their role is fundamental in building up a powerful photovoltaic industry, able to face energy challenges.

We present in Figure 3, a schematic of the total fabrication processes leading to a solar cell.
The first step, pertaining to the metallurgical industry, is the reduction of the quartz with coal to produce the 98% pure metallurgical silicon (with some production of CO_2, a very small amount per PV kWh to be generated in the future).

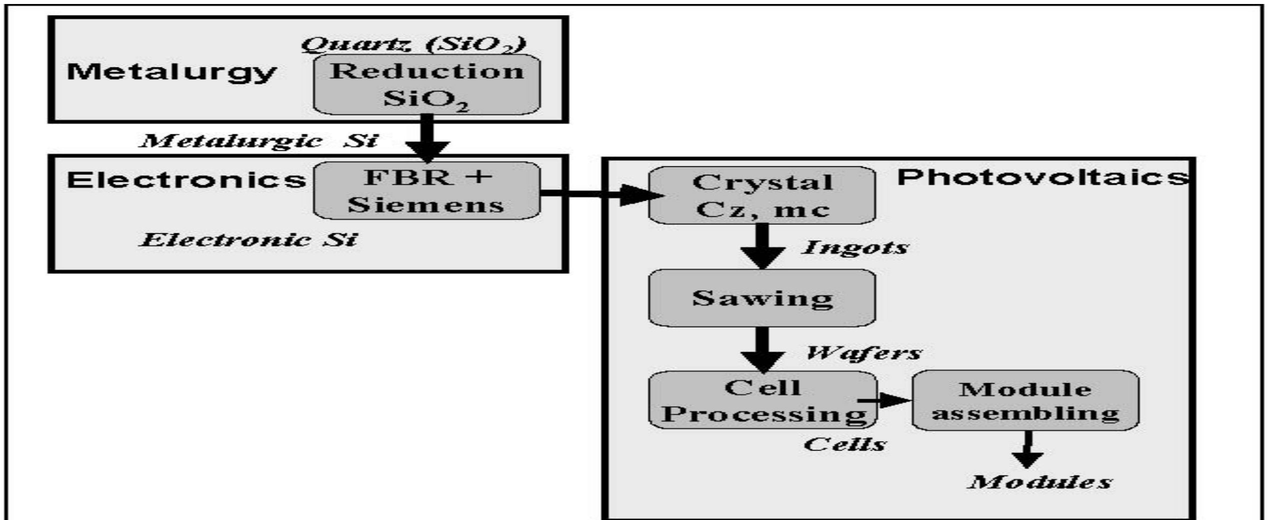

Figure 3. Industrial steps to a solar cell

From this metal, the industry produces about 1 million tm per year[11] at a cost of about €1/kg. Part of this, is purified to produce some 20000 tm of electronic grade silicon for the use of both the electronic industry and the PV industry. The purification procedure is done in three steps. First the silicon is treated at moderate temperature (≈300 C) with HCl to produce liquid chlorosilanes that are subsequently purified by fractional distillation. Finally the pure chlorosilanes are reduced at high temperature (≈1200 C) with H_2 to produce electronic grade silicon, also called polysilicon, with impurities in the range of 0.1-1 ppb. The price of this polysilicon is of about €50/kg. Out of the 20000 tm of polysilicon, some 4000 goes to solar cells fabrication. Very often the PV industry accepts the ultrapure silicon rejected by the electronic industry at a price that may be around €5-15/kg.

The polysilicon is then molten and grown by the PV industry into single crystal (or mono-crystalline) ingots by the Czochralsky method or into multi-crystalline blocs by a variety of directional solidification methods, so that big grains can be formed. These blocs, either mono- or multi-crystalline, are then cut into wafers or, alternatively, the molten silicon is grown into sheets that do not require any further cutting. In 2002, 36.4% of the solar produced were from cut monocrystalline wafers, 51.6% from cut multicrystalline wafers and 4.7% were grown sheets.

The processing of the solar cells itself is presented in Figure 4. The wafer comes doped with boron from the crystal growth step. This produces in the wafer the so-called p-type conductivity and facilitates a selective contact to the valence band. The wafer is treated with an anisotropic etch (mainly NaOH) to make the surface rough , to present a better absorption of the light. Then it is exposed at high temperature (≈850 C) to vapours containing phosphorus, in such a way that a surface layer of about ½ of micrometer is doped with this element. This facilitates the selective contact to the conduction band. The deposition of one quarter of wavelength layer of TiO_2 (or other materials) allow to further reduce the reflection of light. Finally contacts with metallic grids are formed on both faces.

The process described, leading to cells of 15% efficiency in mono-crystalline wafers and 13% in multi-crystalline ones, is used with small variations by the large majority of solar cells manufacturers[12].

Finally the cells are tested and classified : cells of similar performances are integrated bonded to tined copper ribbons so that the front face of one cell (forming the negative electrode) is connected to the rear face of the next one (the positive electrode) thus forming strings of series

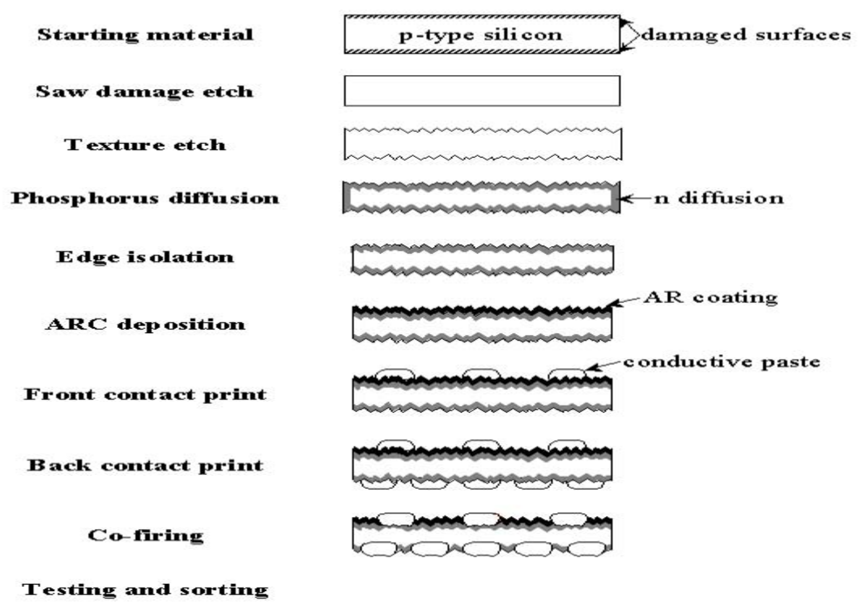

Figure 4. Fabrication process of silicon solar cells

connected cells that are sandwiched by transparent polymer layers in its monomer state . The whole sandwich is placed in a glass pane and covered by a protective sheet. Then the assembly is heated and the monomer melts and polymerizes so that the whole ensemble becomes intimately bound together.

The cost of a PV module is today in the range of €3/Wp. Of this, *roughly*, 20% corresponds to the cost of the hyper-pure polysilicon, 20% to the growth of the crystal, 20% for sawing the ingots into wafers, 15% for processing the solar cells and 25% for assembling the cells into modules. Of course, the preceding figures, vary from factory to factory and from technology to technology. In multicrystalline cells, the crystal growing is expected to be proportionally smaller but as, the efficiency is also smaller, the cell cost per rated watt is very similar. A recent study[13] on the costs aspects has confirmed that the most important single actions to reduce the costs of solar cells is to increase the efficiency or to reduce the cell thickness so as to get more cells form the same ingot.

Efficiencies up to almost 25% have been obtained in laboratory with processes that require about four times more operations than the process described. Increasing the number of operations is negative, not so much due to the costs of the new operations, but because the yield of the fabrication decreases. Here yield refers to the fraction of the number of cells successfully encapsulated into modules to the number of wafers that started the cell processing. Although the yield is a figure jealously hidden by the manufacturers, in the standard process described above, the yield is above 95% in good manufacturers. The yield is reduced mainly by malfunction or unacceptable low efficiency of the cells or by breakage of wafers during the processing.

The yields in the PV industry tend to be much better than in the electronic industry, so that it is to be feared that the 25%-efficiency cells, if fabricated, might have a yield much lower and therefore would not be cost effective. In any case, only very few of the major companies (mainly Sanyo, BP Solar, and Sharp) are commercializing high efficiency cells based on different processes. The HIT (Heterojunction with Intrinsic Thin layer) cells of Sanyo are based on the use of tandem cells of amorphous and crystalline silicon together. This concept will be explained later. However nobody outside Japan seems to be able to reproduce their results, so that what they do is not well understood. Obviously, the use of thinner cells affects negatively the yield. Only one of the major companies (Photowatt) is, to our knowledge, commercializing cells thinner than usual (150 instead of 300 μm).

Therefore, in the field of cell processing, there is a need of R&D to develop more efficient and/ or thinner cells that can be fabricated at high yield. It is difficult to undertake this R&D activity in absence of a close contact with the cell manufacturers.

The use of silicon ribbon seems a clear way of reducing the cost of the cells as it makes unnecessary the expensive wafer sawing process. But again here, slow growth of the sheet makes it expensive and its irregular surface termination makes difficult to apply the ordinary cells technology without breakage. Only one of the major companies (RWE) produces commercial cells based on this technology and the relative presence of this type of cells in the market, though small, seems to be decreasing.

The assembling of cells into modules, in the way described above, is conceptually rather labor consuming. Indeed some companies have developed clever automation processes. However some R&D attempts to develop solar cells connected on the rear side (Sunpower) are under way and this would be completed by some kind of planar interconnection.

Silicon is one of the most abundant elements in the earth (actually the second most abundant after oxygen in the lithosphere).So far the PV industry has adapted itself to the silicon fabricated for the electronic industry, in part by using off-specifications polysilicon or the remnants of the crystal growth. The size and growth-speed of the PV industry suggests that time is ripen for developing a hyper pure-silicon better adapted to the needs of the PV industry.

May be it would be possible to overcome the expensive chlorination-distillation-reduction path and find a more direct path form metallurgical silicon to solar silicon, or at least to use the classical path in a way more adapted to the solar silicon needs. R&D on both schemes is under way. On the other hand it seems inefficient to reduce the silicon after purification into solid polycrystalline bars that are subsequently crushed and molten, solidified again and cut into wafers. Would it not be possible to reduce the hyper-pure chlorosilanes into the solar wafer that will support the solar cell itself? Alternatively, would it not be possible to melt the metallurgical silicon and to purify to the needed level before growing the PV crystal? Again R&D in both directions is underway.

AIII-1.4 Thin film solar cells

Silicon is so far the indisputable winner in the conquest of the PV market but it has been long ago claimed that silicon is a poor PV material. Other semiconductors such as Cu_2S and today $Cu(InGa)Se_2$ or CdTe are considered as better PV materials. They absorb the light more effectively and allow the fabrication of thin film modules. These are of interest because, in principle, the thin film can be a material rather poor —not like the hyper-pure silicon— due to the fact that the electrons are pumped up in positions very close to the selective contact that extract them from the solar cell.

The use of Cd in all of them (as absorbent in some cases and as electrode in others) rises some concerns on environmental friendliness but the issue has been carefully studied with positive conclusions. We should also mention silicon in its amorphous form, that also allows the formation of thin film modules. For all of them the potential manufacturing costs of PV modules has been considered rather low.

The latter, has known a non-negligible level of industrialisation but has lost momentum by its fundamental performance degradation and the low efficiency obtained. The $Cu(InGa)Se_2$ and CdTe cells that have given good efficiencies in laboratory are considered as very promising but have not been able to be fabricated in sizeable amounts despite copious investment done for the purpose. Most probably, the reason is the low yield. Probably, attempts to build production lines after the promising laboratory results, have faced the need of disposing too often the whole production due to module malfunction. This is a pity because in the thin film technologies the product is not a cell but a full module with all their interconnections made at the same time by laser in a planar and quasi-continuous way very prone to achieve low costs. There is a big, but decreasing, R&D effort in all these types of thin film cells.

Another type of potentially low cost PV module is based on the dye-sensitised cells. Such cells are based on a dye adsorbed on the surface of a large gap semiconductor such as titanium dioxide and immersed in an electrolyte (that can be embedded in a gel) with a transparent counter-electrode in the front. The dye absorbs a photon and is able to pump an electron to the Ti conduction band. From there it is contacted to the external circuit where it produces useful work. Then the electron returns to the electrolyte and finally to the dye through a redox reaction that leaves the dye ready for a new photon absorption. The alleged advantage of this technology is its low potential cost, based on a low temperature wet chemistry (in contrast to the high temperature fabrication processes of ordinary solar cells). Efficiencies are still low and reliability is suspected to be poor. Despite several attempts, no product based on this technology has relevant presence in the market.

The preceding cells are often called organic solar cells but today there is also research on solar cells based in organic conductors, some of which have semiconducting properties. The principles are similar to those given at the beginning but the semiconductor used and the way for selective contacts to the high end low energy electrons are based on chemical reactions. Again is a product to be fabricated at low cost although the performance is still very low.

AIII-1.5 Next generation solar cells

Though the solar resource is immense, its flux is moderate. This is the ultimate reason of its high cost. Under this circumstance, the solar power flux must be used most effectively. A new generation of solar cells must be developed with this aim in mind.

Conventional solar cells use the solar resource ineffectively. Letting aside the loss mechanisms already mentioned, of light reflection and shading, non-radiative recombination and ohmic losses, that in good cells are greatly reduced, some fundamental loss mechanisms remain.

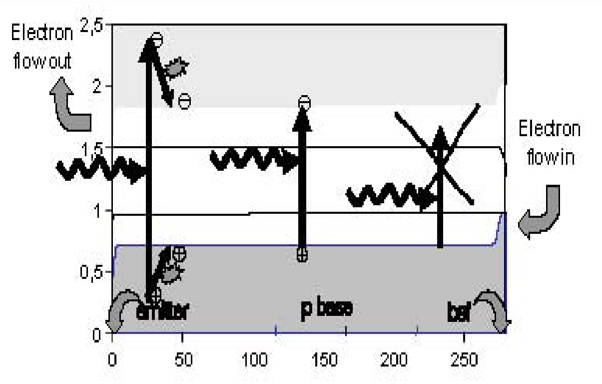

Figure 5. Schematic of the operation of a solar cells and energy loss processes.

As represented in Figure 5, only the photons with energy close to the cell band gap are converted into electricity effectively; the photons with less energy are not converted at all, and of those with energy well above the band gap only the energy close to the band gap is effectively recovered. Taking these into account the top efficiency of a solar cell is 40% at 300 K for isotropic illumination —achievable by means of an ideal concentrator (concentrating ≈46000 times!)— with radiation at 6000 K (close to that of the sun's photosphere) or 33% under normal unconcentrated (standard) sunlight at the Earth's surface[14].

The most obvious way of overcoming this drawback is to fabricate stacks of cells of different materials as the one represented in Fig 6. In this case, three separate cells are built together (monolithic stack), one of GaInP, one of GaInAs and one of Ge having gaps of 1.68, 1.18, and 0.69 eV respectively. The photons with energy below 1.18 eV are converted in the lower cells (Ge), those between 1.18 and 1.68 in the GaInAs cells and the rest in the upper cell. Every cell connects the valence band of the upper cell to the conduction band of the lower cell by means of the so called tunnel junction. The voltage appearing across the whole stack is the sum of the voltages of the individual cells. On the contrary the current is smaller because a small fraction of the solar spectrum is converted in each cell, but the efficiency is high. In the best case it is of

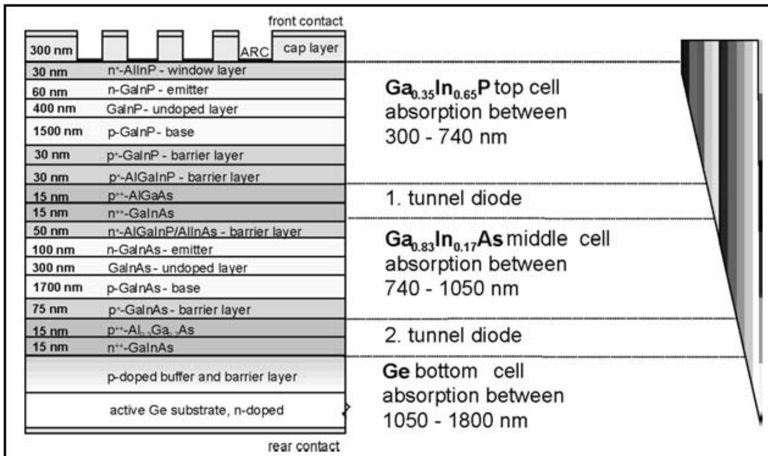

Figure 6. Triple cell stack for high efficiency

36.5% at a concentration level[15] of 100. 40% without concentration is the expected efficiency if one finds a suitable material with a 1.0 eV gap but finding it has become a more difficult task than expected.

The efficiency limit of the tandem or cells stack concept, under the same assumption used for a single cell, and infinite number of cells[14] is 86%, This proves the high efficiency potential of the concept.

It is worth mentioning that this technology is commercial for space cells. Furthermore, the Sanyo's HIT technology is based in the joint utilisation of crystalline silicon with a band gap of 1,1 eV and the amorphous silicon with a gap of 1.7 eV. Also the amorphous silicon cells use in some cases multi-junction cells, based on amorphous Si, Si-C of higher band gap and Si-Ge of lower band gap.

Martin Green has probably been the first to bring the attention to the need of developing new concepts in PV. In 2000, he has obtained a grant form the Australian government to create the so called Centre for Third Generation Photovoltaics. He has recently given an overview on the topic[16] An integrated Project, named FULLSPECTRUM, has been granted by the EU with € 8.4 million in 5 years, for the R&D of the next generation of photovoltaic concepts that may exceed the fundamental efficiency limitations affecting the prevalent solar cells through a better utilisation of the solar spectrum. Coordinated by the Universidad Politécnica de Madrid, it involves 19 European centres, including the most prestigious ones.

The multicell stacks (multi-junction cells) is one of the topics to study in this consortium. Other topic is the thermo-photovoltaic conversion[17]. In this case, the Sun heats a receiver that becomes a radiator. Its radiation is converted by a solar cell. The reason why this concept has high efficiency potential is because the radiation of non appropriate energy can be reflected back to the radiator, keeping it hot so that only the appropriate photons are retrieved for effective conversion. The concept predicts efficiency limits of 84%[14] but the photon recycling necessary for high efficiency is far from being loss free and reaching high efficiencies in practice is an arduous task.

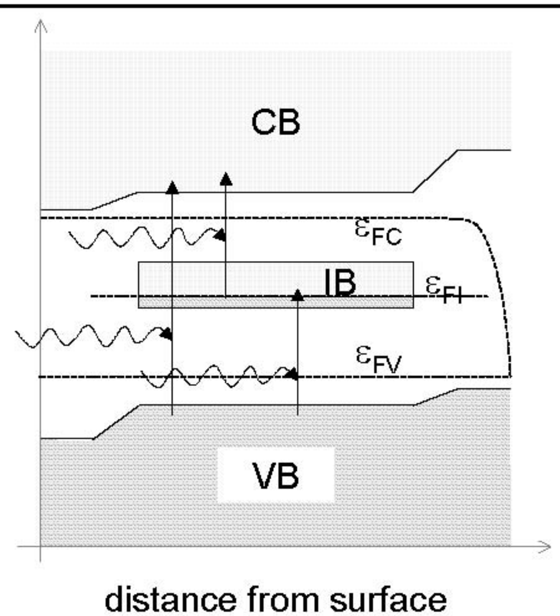

Figure 7. Band diagram of an intermediate band solar cell

Novel concepts are also contemplated in FULLSPECTRUM. A promising one is the intermediate band solar cell (IBSC)[18]. It is based on developing a material with an intermediate band located within the band gap and well separated form valence and conduction bands. As represented in Figure 7 the intermediate band solar cell will consist on a layer of the indicated material situated between two layers of ordinary semiconductor of n and p conductivity intended to produce selective contacts to the valence and the conduction bands respectively[19]. In this cell the photons are pumped form the valence band to the conduction band either by one photon of enough energy to produce the transition or by two photons of smaller energy, one pumping the electron from the valence band to the intermediate band and another from there to the conduction band. The limit efficiency of this concept is 63.2%[18].

Intermediate band materials can be fabricated with arrays of quantum dots[20]. In collaboration with the University of Glasgow, we have fabricated IBSC with this technology[21] and demonstrated all the basic operations of the IBSC. However, the efficiency is smaller that the samples without the quantum dots due to two reasons: we have deposited few layers of QDs and the non radiative recombination mechanisms are too strong and must be reduced. Alloys presenting an IB have been recently found at the Berkeley National Laboratory[22].

Organic cells using two-photons mechanisms is another subject of research in Full-spectrum[23]. This would converge with the present effort in developing organic semi-conductors and is thought to provide the efficiency potential lacking in the cells made with these semiconductors. However the research on this topic is still incipient.
There are other potential novel concepts not contemplated in Fullspectrum. Among them, the attempt of extracting energy from the electrons by selective contacts before they thermalize with the semiconductor network[24]. The potential of this concept is 84% but nobody knows how to proceed.

Many of the most efficient solar energy converters are the product of sophisticated operations and will not likely be appropriate for low cost manufacturing. Concentrators may bring them to competitive costs. Concentration ratios of 1000 are being attempted in Fullspectrum for its use with the highly efficient stacks of cells. The use of novel optical designs[25], based on the Hamiltonian formalism of the geometrical optics (anidolic optics), may render the use of this high concentration rather cheap.

AIII-1.6 Conclusions

To summarize, we think that PV will become a major (but not single) electricity supply by mid of this century, at costs that will be competitive with concurrent electricity technologies. It has potential for it and the present fast commercial development seems to prove a social implication towards this goal.

But this will not be possible without a serious R&D activity, whose nature has been discussed along this paper and that is summarized in Table I. For a more detailed summary of the present status of the R&D in PV see the summary of the last world conference at http://www.wcpec3.org/.

Table 1. Summary of the R&D needs in PV

Topic	R&D with industry	Economic interest	R&D activity	Comment
Silicon purification Growth	desirable desirable desirable	confirmed confirmed confirmed	low low medium	Develop dedicated purification Avoid freezing/melting steps Ribbon or sheet (avoids sawing); watch subsequent processing
Sawing	compulsory	confirmed	medium	Cut thinner wafers
Cell processing	desirable	confirmed	high	Higher efficiency, thinner wafers
Thin film cells	desirable	doubts	high	Higher efficiency, stability, manufacturability.
Next generation	indifferent	supposed	medium	Cells stacks(MJC): increase the very high efficiency; develop cheap concentrators IBSC: prove efficient operation
	indifferent	unknown	medium	IBSC: prove efficient operation
	indifferent	unknown	low	Thermophotovoltaics: prove efficient operation
	indifferent	unknown	very low	MBC: prove concepts
	indifferent	unknown	very low	Hot electron cells: prove concepts
	indifferent	unknown	negligible	PV rectennas: prove concepts

Most probably, the quickest way of reaching this mass production of electricity is the development of a next generation of PV converters with a better use of the solar spectrum and therefore with a quicker learning curve that the one of the present Si PV technology.
But we cannot discard that the present Si technology could reach already the desired goal if society is willing to support this technology under uncompetitive conditions for a time long enough and with a sufficient level of support. Also in this case the R&D will be an essential tool in the cost reductions and therefore in the market expansion.

For a more detailed view of the strategy to follow, look at references 26 and 27.

[1] Paul Maycock, PV News, February issue, successive years

[2] Paul Maycock, PV News, (February 2003), 2

[3] Photon International, (March 2003), 42

[4] Photon International, (March 2002), 38

[5] Paul Maycock, Renewable Energy World, 3, 59, (2000)

[6] V. Parente, J. Goldemberg and R. Zilles, Prog. Photovolt. 10, 571, (2002)

[7] A. Luque, Prog. Photovolt. 9, 303, (2001)

[8] H. Kelly and C.J. Weinberg, in T.B. Johansson, H Kelly, A.K.N. Reddy, R.H. Williams and L Burham eds. Renewable Energy, Sources for Fuels and Electricty, (Island: Washington 1993) 1011.

[9] K. Knapp and T. Jester, 16th EC. Photovoltaic Solar Energy Conf., 2053, (2000).

[10] "Exploring the Future. Energy Needs, Choices and Possibilities. Scenarios to 2050" (Shell International 2001), www2.shell.com/home/media-en/downloads/51852.pdf

[11] B. Ceccaroli and O. Lohne, in A. Luque and S. Hegedus eds. Handbook of Photovoltaic Science and Engineering, (Wiley: Chichester, 2003), 153.

[12] I Tobías C del Cañizo and J Alonso. in A. Luque and S. Hegedus eds. Handbook of Photovoltaic Science and Engineering, (Wiley: Chichester, 2003), 256.

[13] A. Rohatgi, 3rd World Conference on Photovoltaic Energy Coversion, (in press)

[14] A. Luque and A. Martí, in A. Luque and S. Hegedus eds. Handbook of Photovoltaic Science and Engineering, (Wiley: Chichester, 2003), 114.

[15] T. Takamoto et al. "Multijunction solar cell…" Proc. 3rd World Photovoltaic Energy Conversion Conference, (Osaka, 2003, to be published).

[16] M. A. Green, Third Generation Photovoltaics: Advanced Solar Energy Conversión, (Springer Verlag, 2003)

[17] V.M.Andreev, V.A.Grilikhes, V.D.Rumyantsev, Photovoltaic Conversion of Concentrated Sunlight, (Wiley: Chichester, 1997).

[18] A.Luque and A.Martí, Phys. Rev. Lett., 78, 5014 (1997).

[19] A. Luque, A. Martí, Progr. in Photovoltaics, 9, 73-86 (2001)

[20] A. Martí, L. Cuadra and A. Luque, Proc. 28th Photovoltaics Specialists Conf., (IEEE: New York, 2000), 940

[21] N. López, D. Zhou, L. Cuadra, C. Stanley, A. Mckee, A. Martí and A. Luque, "Analysis of Experimental", III Congreso Nacional de Dispositivos Electrónicos, CD III-15 (Self-published CD: Barcelona, 2003) paper 15

[22] G. Yu, W.Walukiewicz, J.Wu, W.Shan, J.W. Beeman, M.A. Scarpulla, O.D.Dubon , P.Becla. "Diluted II IV", Phys. Rev. Lett., to be published

[23] M. Späth, J.M.Kroon, P.M.Sommeling, J.Wienke, J.A.M van Roosmalen, T.B. Meyer, A.F. Meyer, O. Kohle. Proc. 26th IEEE Photovoltaic Specialists Conf., (IEEE: New York, 1997) 503.

[24] P. Wurfel, Sol. En. Mat. Sol. Cells, 46, 43 (1997).

[25] J.C. Miñano, JC. González and P. Benítez, Appl. Opt. 34, 7850 (1995)

[26] A. Luque and A. Martí in A. Marti and A. Luque eds, Next Generation Photovoltaics. (IOP: Bristol 2004),

[27] Zh. I. Alferov and V.D. Rumyantsev, in A. Marti and A. Luque eds, Next Generation Photovoltaics. (IOP: Bristol 2003), 19

AIII-2 STORAGE OF ELECTRIC ENERGY

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AII-2.1 Batteries: Present and Future

AII-2.1.1 Near term

In the near term (5-10 years), it is expected that batteries possessing enhanced energy and power densities as well as lifetimes will be needed to enable hybrid/electric vehicles having performance characteristics comparable to conventional internal combustion (IC) engine/ petroleum fueled vehicles. Present state-of-the-art technology using Li batteries offers the highest energy densities [twice that of NiMH batteries that are used in hybrid and electric vehicle (EV) technology] and cycle life, but the components, including cathode, electrolyte and separator, are costly. Provided improvements to energy density over current Li technology can be made, batteries might still be used as the primary power source for a pure electric vehicle. In any event, high energy density systems with high cycle life will still be necessary. Even for hybrid technology, batteries are a vital part of the overall power system for hybrid vehicles that utilize regenerative braking. Candidate systems based on Li battery technology offer the highest known energy densities available, but these systems still fall short of automotive design goals that would make such vehicles competitive with petroleum-based systems. An effort to better understand and design suitable cathodes, anodes and separators for Li batteries would benefit the transportation sector as well as the area of portable electronics.

Lead-acid battery technology, which was developed nearly 150 years ago, is still being used for vehicular applications. These batteries have a gravimetric density of 0.16MJ/kg and 0.25 MJ/L. Ni metal- hydride batteries have gravimetric and volumetric energy densities nearly twice that of lead-acid, and Li batteries (0.5MJ/kg and 1MJ/L) have values twice that of NiMH. At present, it is difficult to imagine improving on the energy density of Li batteries unless improvements to cathodes (typically $LiCoO_2$) are found. Incremental improvements are on the horizon through partial substitution of Co by Ni yielding ~15% improvement in charge capacity (resulting from the phase stability of $LiNi_{0.8}Co_{0.2}O_2$ to retain a stable phase to discharge levels to $Li_{0.4}$). Longer term goals aimed at improving energy density in Li batteries should consist of studying Li insertion/de-insertion kinetics and phase stability of both cathodes and anodes in non-Co based materials. Also, Li-based systems have specific charge/discharge requirements requiring specialized electronics designed to control limits and rates for each cell of a battery pack. Cathodes and anodes that offer the possibility of higher robustness to high discharge rates and overcharging may allow for the simplification of Li-based systems. For instance, Li_2S-based systems demonstrate such robustness and have shown capacities as high as 0.65MJ/kg. A combination of doubling of the energy density of Li secondary (rechargeable) batteries in conjunction with robust cathode/anode systems would be the enabling factors in implementation for the transportation sector as well as offer huge benefits for other sectors like portable electronics.

High interface per volume materials offer other special advantages in the energy storage arena as well, particularly for advanced secondary battery technologies. For instance, nanoscale active electrode composites (Li-alloying metal nanoclusters, Li-insertion metal oxide or metal phosphate nanoparticles) self-assembled in a polymer ion-conducting matrix could enable all solid, thin film batteries capable of high current rates, while accessing the full theoretical capacity of the active electrode material. The use of nanoscale active components offers further promise to dramatically extend cycle life of rechargeable batteries by enhancing stability to volumetric excursions that cause decrepitation of bulk electrodes.

Reference:
"Basic Research Needs to Assure a Secure Energy Future," A Report from the Basic Energy Sciences Committee, February 2003, http://www.sc.doe.gov/bes/BESAC/reports.html.

AII-2.1.2 Key questions

Key questions are what phenomena limits performance, the need for understanding interfacial phenomena, how to make stabile interfaces, and the role nanomaterials can play in batteries. Needs include understanding the behavior of electrodes active materials, syntheses of better materials and electrodes, the need to have both electronic and ionic conductance in the same materials in the electrode. The polymer electrolytes are not thermodynamically stable and this allows both chemical and electrochemical reactions at the electrodes. There is a need to prevent these reactions.

AII-2.1.3 Recommendations for future work include

- Modelling, computation chemistry, molecular simulation and mechanistic studies are important tools used to guide experimental development of materials, components and cells. Modeling of thermal processes to predict safety-related problems is needed. Use of modeling to scale up components, cells and batteries is a necessary tool to guide the experimental development efforts.
- Exploratory studies to identify systems other then lithium should be started because of the potential for lower cost, longer life and superior performance.
- There is a need to make new active materials, electrolytes, interfacial films, coating for electrodes. While battery developers are skilled at using materials and physical chemists are skilled at characterization of active materials and other components in cells, it requires a different type of skill to make molecules. The list of needs include improved room temperature electrolytes, composite polymer electrolytes, protective coatings for anodes and cathodes, interfaces with mixed electronic and ionic conduction, control of orientation of materials, and redox shuttles.
- The application of solid-state physics and chemistry is needed to understand the processes occurring in advanced battery systems. The application of the new diagnostic methods such as nuclear magnetic resonance, neutron diffraction, X-ray diffraction are needed to characterize and improve the performance of cell components and cells.
- Good thermodynamic data is needed for modeling. Input from the battery developers is needed to prioritize what data is needed.

Reference:

"Interfaces, Phenomena, and Nanostructures in Lithium Batteries, Proceedings of the International Workshop on Electrochemical Systems," Proceedings Volume 2000-36, Editors A. R. Landgrebe and R. J. Klingler.

AII-2.1.4 Electro-chemistry

In electrochemistry, understanding what controls electrode and electrolyte performance is key to future improvements in electrochemical components used in electronic devices, telecommunications, satellites, solar and wind energy utilization, electric power production, and electric and hybrid vehicles. Scientific challenges include the theory, the computational or experimental ability to understand the role of interfaces in electrochemical processes. The limited understanding of electrochemistry at the interface of dissimilar solids and phases and at buried interfaces is hindering progress in achieving high power and low cost systems needed in electric and hybrid vehicles, for effective use of wind and solar energy sources, and for distributed power generation by chemical fuel cells. Scientific opportunities deal with the emergence of the ability to control electrode structures on the nanometer scale. Preliminary studies have shown that this has a great impact on the electrochemical efficiency of electrode processes and the rate at which they respond to electrochemical potentials.

Reference:

BES CRA of Chemical Energy and Chemical Engineering
Dr. Paul H. Maupin, Program Manager
E-mail: paul.maupin@science.doe.gov

AII-2.1.5 The Electric Power Systems Research and Development

The Electric Power Systems Research and Development program includes the following battery system demonstration projects:

An advanced battery system has recently been installed at S&C Electric, Chicago's largest manufacturing plant. The truck size 2 MW battery will protect an extrusion plant where high voltage insulators are molded. Such processes are particularly vulnerable to short power outages, because the entire run must be discarded and equipment may be severely damaged. With the new system, power supply will continue seamlessly when an outage or voltage sag happens. The system has been estimated to prevent production losses of approximately $500,000 dollars annually - representing a one year payback. Similar systems could go far in increasing electricity reliability and protecting the most vulnerable industries such as semiconductor and pharmaceutical plants.

The Puerto Rico Electric Power Authority currently operates the largest Battery Energy Storage System in the world with an output capacity of 20 MW and 14 MWh of stored energy. This facility provides spinning reserve in case of a generator outage and contributes frequency regulation for the San Juan metropolitan area. The utility has recently decided to repower the facility and to double the amount of storage by building a second 20 MW system.

Reference:

Office of Electric Transmission and Distribution's Electric Power Systems Research and Development program

http://www.electricity.doe.gov/program/electric_rd_estorage_projects.cfm?section=program&level2=estorage

Further References:

[1] Links to the following manuals are all available at http://ev.inel.gov/battery.These documents provide a good general basis for understanding the performance requirements for electric and hybrid electric vehicle energy storage devices.

FreedomCAR 42V Battery Test Manual

FreedomCAR Battery Test Manual for Power Assist Hybrid Electric Vehicles

PNGV Battery Test Manual, Revision 3

Electric Vehicle Capacitor Test Procedures

USABC Electric Vehicle Battery Test Procedure Manual, Revision 2

[2.] The internet site for the Batteries for Advanced Transportation Technologies (BATT) program at http://berc.lbl.gov/BATT/BATT.html includes quarterly and annual reports. This program addresses many long-term issues related to lithium batteries, including new materials and basic issues related to abuse tolerance.

[3] Zhou, J., et al., "Interfacial Stability Between Lithium and Fumed Silica-Based Composite Electrolytes," Journal of the Electrochemical Society, 149(9):A1121-A1126, 2002. (Addresses issues related to the formation of Li dendrites.) (ISSN: 0013-4651) (Available via Electrochemical Society Web site at:

http://ojps.aip.org/JES/?jsessionid=2984621059489204943 On menu at left, select "Browse all JES issues," and then "Volume 149." Scroll down to September 2002, Issue 9, and select either TOC, from which you may access article.)

References 4 and 5 discuss issues related to more mature, high power, lithium-ion batteries. They include information about cell chemistries that have proven to be useful model systems for these applications along with discussions of issues related to abuse tolerance and cell life.

[4] FY 2000 Progress Report for the Advanced Technology Development Program, U.S. DOE, Office of Advanced Automotive Technologies, December 2000.,

http://www.cartech.doe.gov/pdfs/FC/97.pdf

[5] Advanced Technology Development (High-Power Battery): 2001 Annual Progress Report, U.S. DOE, Office of Advanced Automotive Technologies, February 2002

http://www.cartech.doe.gov/pdfs/B/196.pdf

[6] Information about requirements for vehicular batteries, separators for lithium-ion batteries, and abuse testing can all be found at the USABC section of the USCAR internet site. Go to http://www.USCAR.org; click on "Teams"; scroll down and click on "United States Advanced Battery Consortium (USABC)". This site provides a second source for many of the documents found at reference 1.

[7] The abuse test procedures, developed for FreedomCAR by Sandia National Laboratories may be accessed directly at:

http://www.uscar.org/consortia&teams/USABC/SAND99-0497%20USABC%20Safety%20Manual.pdf

Amatucci, G. G., et al., "Polyvalent Intercalation Batteries, a Step into Next Generation Energy Storage," presented at the 198th Meeting of the Electrochemical Society, Phoenix, AZ, October 22-27, 2000, Abstract No. 215, Meeting Abstracts, Vol. MA2000-2, Electrochemical Society, 2000. (ISSN: 1091-8213) (Paper published under new title: "Investigation of Yttrium and Polyvalent Ion Intercalation into Nanocrystalline Vanadium Oxide," Journal of the Electrochemical Society, 148(8):A940-A950, 2001. (ISSN: 0013-4651) (Available via Electrochemical Society Web site at: http://ojps.aip.org/JES/?jsessionid=2984621059489204943. On menu at left, select "Browse all JES issues," and then "Volume 148." Scroll down to August 2001, Issue 8, and select either TOC from which you may access article.)

AIII-2.2 Energy storage

In the United States, and some other countries, demand for electricity varies during the day, with peaks during daylight and early evening and much less of a demand late at night and early in the morning. This has led to electricity generating companies developing systems to store energy produced in the low demand periods to be recovered during the periods of increased demand. These storage systems include pumped storage, compressed air energy storage, flywheel energy storage, and superconducting magnetic energy storage. The following covers the first two of these systems since they are in use for large scale generation whereas currently the other two are used for small scale generation.

- Pumped Hydro[1]:

From 1929 until 1970 it was the only commercially available storage option for generation applications. Conventional pumped hydro facilities consist of two large reservoirs, one is located at base level and the other is at a higher elevation. Water is pumped to the upper reservoir where it can be stored as potential energy. Upon demand, water is released back into the lower reservoir, passing through hydraulic turbines that generate electricity. The barriers to increased use of this storage technology in the U.S. include high construction costs and long lead times as well as the geographic, geologic and environmental constraints associated with reservoir design.

- Compressed Air Energy Storage (CAES)

CAES plants use off-peak energy to compress and store air in an air-tight underground storage cavern. Upon demand, stored air is released from the cavern, heated and expanded through a combustion turbine to create electrical energy. Currently, manufacturers can create CAES machinery for facilities ranging from 5 to 350 MW. EPRI has estimated[2] that more than 85% of the U.S. has geological characteristics that will accommodate an underground CAES reservoir. Studies have concluded that CAES is competitive with combustion turbines and combined-cycle units, even without attributing some of the unique benefits of energy storage.

- Pumped Storage

A pumped storage system consists of two reservoirs, located at different elevations, a system to pump water to the higher elevation, and a turbine system to generate electricity when water is released to return to the lower system. A reversible turbine/generator enables the same system to act as an electric pump and as an electricity generator. The major advantages are the ability to store energy using off-demand and therefore lower cost electricity and the rapid recovery, with hundreds of MW being available in about one minute. The disadvantages are the need to find appropriate sites and the large construction costs for what usually are smaller capacity systems. The first use of pumped storage was in Italy and Switzerland in the 1890's. In 2003, there was 100 GW installed in Europe,

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1 Electric Power Research Institute, Compressed Air Energy Storage: 1994. EPRI Brochure BR-102936.

2http://www.uscar.org/consortia&teams/USABC/SAND990497%20USABC%20Safety%20Manual.pdf

Asia, and Latin America and 21 GW installed in Japan.[3] In 2000, the United States had 19.2 GW installed capacity of pumped storage.[4] Since power is used to pump the water to the upper reservoir, the net generation capacity is less than these numbers.

An encyclopedia[5] gives the following as the worldwide list of pumped storage facilities:

Australia

Bendeela, 80 MW
Jindabyne Pumping Station
Kangaroo Valley, 160 MW
Tumut Three, (1973), 1,500 MW

China

Guangzhou, (2000), 2,400 MW
Tienhuangping (2001), 1,800 MW

Germany

Goldisthal (2002)1,060 MW
Markersbach (1981), 1,050 MW

Ireland

Turlough Hill 292 MW

Italy

Piastra Edolo (1982), 1,020 MW
Chiotas (1981), 1,184 MW
Presenzano (1992), 1,000 MW
Lago Delio (1971), 1,040 MW

France

Grand Maison (1997), 1,070 MW
La Coche, 285 MW
Le Cheylas, 485 MW
Mortézic, 920 MW
Revin, 800 Mw
Super Bissorte, 720 MW

Japan

Imaichi (1991), 1,050 MW
Kannagawa (2005), 2,700 MW is under construction. When completed in 2005,

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3 "The Commercial World of Energy Storage: A Review of Operating Facilities (under construction or planned)", S. van der Linden, et al., presentation at the Ist Annual Conference of the Energy Storage Council, Houston, Texas, 3 March 2003.
4 Wikipedia, accessed at http://en.wikipeida.org/wiki/Hydroelectric_energy_storage, 20 August 2004.
5 Ibid.

it will be the world's largest pumped storage plant.
Kazunogawa (2001), 1,600 MW
Kisenyama, 466 MW
Matanoagawa (1999), 1,200 MW
Midono, 122 MW
Niikappu, 200 MW
Okawachi (1995), 1,280 MW
Okutataragi (1998), 1,932 MW
Okuyoshino, 1,206 MW
Shin-Takasegawa, 1,280 MW
Shiobara, 900 MW
Takami, 200 MW
Tamahara (1986), 1,200 MW
Yagisawa, 240 MW
Yanbaru (1999), 30 MW is the first seawater pumped hydro power plant.

Russia

Zagorsk (1994) 1,200 MW
Kaishador (1993) 1,600 MW
Dneister (1996) 2,268 MW

Taiwan

Minghu (1985) 1,000 MW
Mingtan (1994) 1,620 MW

United Kingdom

Cruachan, Scotland
Dinorwig, Wales (1984), 1320 MW
Ffestiniog, Wales 360 MW
Foyers, Scotland

United States

Blenheim-Gilboa, NY (1973), 1,200 MW
Castaic, CA (1978), 1,566 MW
Helms, CA (1984),
Lewiston (Niagra), NY (1961), 2,880 MW
Ludington, MI (1973), 1,872 MW
Mount Elbert, 200 MW, 1,212 MW
Mt. Hope, 2,000 MW
Raccoon Mountain, TN (1979), 1,530 MW
Summit Pumped Water Plant, 1500 MW

Other

Siah Bisheh, Iran, (1996), 1,140 MW
Rance River, St. Malo, France 240 MW hybrid pumped water-tidal plant
Drakensberg Pumped Storage Scheme, South Africa, (1983) 1,000 MW.
Juktan, Sweden

- Compressed Air Energy Storage (CAES)[6]

CAES systems use power generated during off-peak hours to compress air into underground reservoirs for storage. As demand for energy increases, the compressed air is retrieved and heated with a gas combustor before being fed into an expansion turbine that drives a generator. The compressor and the turbine are separate components, and each is linked to a motor generator through clutches. When low-cost off-peak energy is available, the clutch between the motor/generator and the compressor is engaged and the motor is used to run the compressor.

A CAES system is made of above-ground and belowground components that combine man-made technology and natural geological formations to accept, store, and dispatch energy through a series of thermodynamic cycles.

Above-ground components

- Five major above-ground components make up the basic CAES installation:
- The motor/generator that employs clutches to provide for alternate engagement to the compressor or turbine trains.
- The air compressor that may require two or more stages, intercoolers and after-coolers, to achieve economy of compression and reduce the moisture content of the compressed air.
- The turbine train, containing both high- and low pressure turbines.
- Equipment controls for operating the combustion turbine, compressor, and auxiliaries and to regulate and control changeover from generation mode to storage mode.
- Auxiliary equipment consisting of fuel storage and handling, and mechanical and electrical systems for various heat exchangers required to support the operation of the facility.

Under-ground components

The cavity used for the storage of the compressed air can potentially be developed in three different categories of geologic formations: underground rock caverns created by excavating comparatively hard and impervious rock formations; salt caverns created by solution- or dry-mining of salt formations; and porous media reservoirs made by water-bearing aquifers or depleted gas or oil fields (for example, sandstone, fissured lime).

According to the Electric Power Research Institute (EPRI), geologic formations in 75% of the United States have the potential to provide reliable underground air storage required for a CAES system.

A CAES system is designed to cycle on a daily basis and to operate efficiently during partial-load conditions. This design approach allows CAES units to swing quickly from a generation to a compression mode. Utility systems that can realize the greatest value from CAES can be generalized broadly as those whose load varies significantly during the daily cycle or whose costs vary significantly with the generation level or time of day. In addition, CAES plants can respond to changing load (provide load following) because they are designed to sustain frequent startup/shut-

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6 Modified only slightly from section 10.1.3 of "A Summary of the State of the Art of Superconducting Magnetic Energy Storage Systems, Flywheel Energy Storage Systems, and Compressed Air Storage Systems", Sandia National Laboratories report SAND99-1854, July 1999.

down cycles. CAES systems also have improved environmental characteristics in comparison with conventional intermediate generating units. Only two CAES systems are in operation today, one in Germany and one in the United States.[7]

Huntorf, Germany CAES System

The oldest operating CAES system is in Huntorf, Germany. It has been in operation since 1978. The Huntorf CAES system is a 290 MW, 50-Hz unit, owned and operated by the Nordwestdeutche Krafiwerke, AG. The size of the cavern, which is located in a solution-mined salt dome, is approximately 8 million ft^3. It runs on a daily cycle with eight hours of charging required to fill the cavern. Operating flexibility, however, is greatly limited by the small cavern size. Compression is achieved through the use of electrically driven compressors. At full load the plant can generate 290 MW for two hours.

McIntosh, Al, USA CAES System

The second CAES plant, owned by the Alabama Energy Cooperative (AEC) in McIntosh, Alabama, has been in operation since 1991. Referred to as McIntosh Unit 1, this CAES system uses an underground cavern located in a solution mined salt dome. The storage capacity[8] is 19 million ft^3 with a generating capacity of 110 MW. Natural gas heats the air released from the cavern, which is then expanded through a turbine to generate electricity. It can provide 26 hours of generation. The McIntosh CAES system utilizes a recuperator to reuse heat energy from the gas turbine, which reduces fuel consumption by twenty-five percent.

The third commercial CAES is a 2700 MW plant that is planned for construction in the United States at Norton, Ohio. This 9-unit plant will compress air to 1500 psi in an existing limestone mine some 2200 feet under ground.[9]

CAES systems, like other energy technologies, have capital and operating costs associated with their purchase, installation, and use. EPRI estimated the total capital cost for CAES plants using salt storage caverns to be approximately $436/kW. Construction costs are greatly reduced when the CAES system is located in an existing salt dome rather than in a formation that has to be mined. In those instances that require mining, water must be pumped into the formation, and brine must be extracted and then processed on the surface. An aquifier-based system may cost less than a salt cavern system, while a hard rock system would cost more, although even a hard rock system would still cost only about half as much as a pumped hydro system, according to EPRI. The cost per kilowatt of hard-rock caverns is approximately 60% higher than that of solution-mined salt caverns. Tejas Power, in a 1997 presentation, estimated the capital costs for construction of a CAES system at $320/kW to $370/kW. In comparison with other energy technologies, CAES system capital costs are somewhat higher than those of a combustion turbine and less than those for natural gas combined-cycle plants. CAES systems allow utilities to operate their thermal base load generation units at higher load factors to

7 "The Commercial World of Energy Storage: A Review of Operating Facilities (under construction or planned)", S. van der Linden, et al., presentation at the Ist Annual Conference of the Energy Storage Council, Houston, Texas, 3 March 2003.

8 The CAES Development Company lists the McIntosh capacity as 10 million ft3: www.caes.net/mcintosh.html, accessed 1 September 2004.

9 From the Electricity Storage Association web site accessed on 1 September 2004: http://www.electricitystorage.org/tech/technologies_technologies_caes.htm

maximize efficiency and lower unit costs. In some circumstances, a new CAES plant may allow a utility to close or curtail the use of an existing intermediate or peaking plant with high operating costs.

A recent comparison of storage options indicates that CAES is more economic than pumped storage[10]:

	Capacity ($/kW)	Storage ($/kWh)
CAES for at least 300 MW	440	~1
Pumped hydroelectric	900	10

Overall, CAES is a mature, commercially available energy storage technology. The barriers to implementation of this technology appear to be economics and gaining the confidence of prospective owners. Several issues must be addressed before hard-rock caverns and aquifers can be successfully used as a site for a CAES system. A reliable control system for the compressor and the cavern must be developed that would shut down the compressor when the cavern is fully charged to prevent inadvertent charging and eventually a blowout. In aquifers, the challenges include the displacement of water to develop air storage and the matching of the airflow characteristics of the turbomachinery and the aquifer. For the storage system to operate according to power plant specifications, the well manifold and the compressor and turbine characteristics have to be carefully matched. Because the turbogroup will most likely be constructed with existing components that would be expensive to modify, the challenge is to design and, if necessary, adjust the well field so that it satisfies a given duty cycle. The distribution and depth of wells will depend greatly on the air flow rates within the aquifer.

One improvement to CAES that is currently being pursued is compressed air storage with humidification (CASH). In CASH cycles, hot water mixes into the compressed air retrieved from storage to saturate and heat it and to increase mass flow at the turbogenerator inlet. This decreases airflow requirements and thus storage volume requirements by 30% for a given electricity outlet. These benefits, combined with waste heat recycling, improve the electricity input-to-electricity-received ratio to 0.5. Currently, the electricity-input-to-electricity-received ratios for CAES systems range between 0.75 and 0.82 (at the cost of additional fuel at a heat rate of about 400 Btu/kWh). Such ratios are lower (and therefore better) than those of other storage technologies that are greater than 1.0. EPRI has explored the possibility of developing a system that would combine coal gasification with a humidification air storage cycle. Humidification in a CASH system increases the MW output by adding moisture to the air. This means that the energy per unit mass flow through the turbine increases significantly. A CASH system promises coal pile-to-bus bar heat rate down to 8100 Btu/kWh and installed capital costs that are below $1000/kW. This is 20’% to 30’% lower than conventional

10 “Toward optimization of a wind/compressed air energy storage (CAES) power system”, J.B.Greenblatt, et al., Princeton University, presented at the Electric Power Conference, Baltimore, MD, 1 April 2004.

coal-fired and low emission pulverized coal plants. In addition, this type of system could potentially provide almost 99% sulfur removal. The high humidification of the combustion air would also result in low NOX formation.

Chubu Electric of Japan is surveying its service territory for appropriate CAES sites. Chubu is Japan's third largest electric utility with 14 thermal and two nuclear power plants that generate 21,380 MWh of electricity annually. Japanese utilities recognize the value of storing off-peak power in a nation where peak electricity costs can reach $0.53/kWh. Eskom of South Africa has expressed interest in exploring the economic benefits of CAES in one of its integrated energy plans.

Prepared from materials provided by members of the Department of Energy's Office of Science, who reviewed this paper for accuracy.

AIII-3 Space Solar Power System (SSPS) Development Status and Future Perspectives

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AIII-3.1 Introduction

Electricity is an energy resource that is essential for our lives. It is generated by several ways such as hydroelectric power, fossil thermal power and atomic power. However, these powers are the center for dispute over the environmental discussion. Under these circumstances, research has been carried out to look into a possibility to build a power station in space to transmit electricity generated in space to Earth in a form of radio waves. The power station is space is referred to as Space Solar Power System (SSPS) in the present paper. It is also called by different terminologies such as Satellite Power System (SPS), Space Power System (SPS), Space Solar Power Station (SSPS) and Solar Power Station (SPS).

The background technology to build such a large-scale structure in space is to be based on space technology and science. Fortunately the field for human life has extended away from Earth, i.e., to space. It is well known that the International Space Station (ISS) is under construction in collaboration with many countries. The ISS will give a unique opportunity for people to experience to stay long time for future living in space. In addition, numerous satellites are orbiting the Earth for the purpose of making our life more convenient.

AIII-3.2 Demand of Solar Power Satellite in the 21st Century

The SSPS depends on technology for a new utilization of radio waves as a method of transmitting electric power to a distant place. Radio has expanded the horizon of human activity in the modern life and is now indispensable media to our daily life. Its main application in the last century and on has been telecommunications. In the present time, radio technology is fully utilized for mobile communications as well as radio links among computers and computer controlled systems. However, radio could also be used for other purposes such as the power transmission in the light of human welfare. In the last century, the mankind experienced the explosive increase of both its Quality of Life (QoL) and its population despite of the two world wars. The explosive increase inevitably requires an exponential increase of the consumption of energy, food and material resources according as the human population increases exponentially. This fact has led us into today's global issues such as global warming, environmental change and rapid decrease of fossil reservoir. Figure 1 schematically shows a simple calculation of shortage of resources of the total resources to maintain the human civilization in 2050. The upper half panel shows the consumption of resources for human life in a relative unit of "QoL ton". A present population in the developed countries is approximately 1 billion, and that in the developing countries is 10 billions, while the QoL in the developed countries is ten times higher than that in the developing countries. Representing the QoL in the developing countries as a unit for the QoL-ton, the total resources consumed by human today including energy, food and materials for daily and industrial demand is 15 billion QoL-tons persons. By the time of the half way of the 21st century, the population in the developing countries will reach 9 billions and their QoL will reach at least three times higher than now. This result in the fact that the total necessary resources needed to maintain the world economy and welfare of daily life of human is 37 billion QoL-tons persons. Such large demand of more than 250% of the today's amount shall not be reached without the destruction of the environment of our mother planet, Earth. It is noteworthy to stress that the demand of electrical power will increase at much higher pace than the other energy demands according as the world is industrialized and computerized.

To maintain the human welfare and current Quality of Life, or ever to avoid perishing disaster

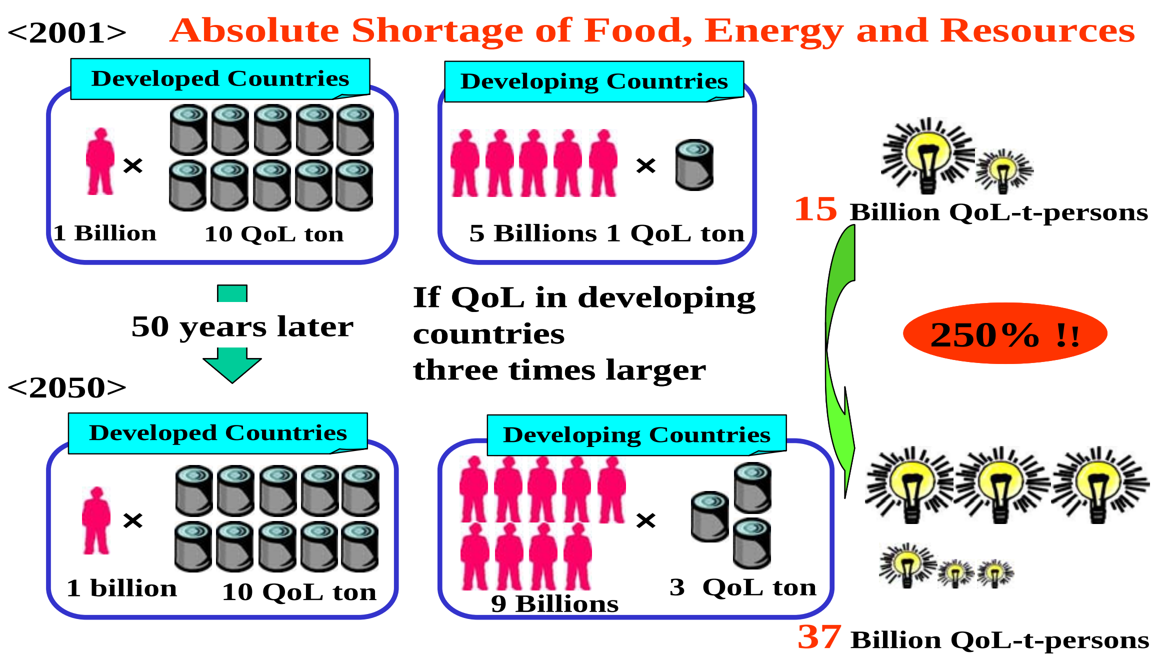


Fig.1 Predicted absolute shortage of resources for human civilization in 2050

during this century, the issues on energy, food and environments should be seriously discussed and solved. The increasing demand for electricity, on the other hand, conflicts with the demand for clean environment due to fossil-based power plant. Therefore the dilemma of these two demands needs to be overcome during the present century. Electricity has been generated by several ways such as hydroelectric power, fossil thermal power and atomic power. However, some of them are the causes of environmental and pollution issues over the globe. Under these circumstances, research has been carried out at Kyoto University and its collaborators to look into a possibility to build a power station in space to transmit electricity generated in space to Earth by way of radio waves.

AIII-3.3 Wireless Power Transmission via Microwaves

It was Nicola Tesla[1,2] who first conceived an idea of wireless power transmission. However his experiment was not successful due to the unavailability of radio waves with sufficiently short wavelengths to beam down to a point or small area target. Yagi and Uda[3] predicted a technical feasibility of power transmission on radio waves foreseeing the era of microwave availability. Microwave technology was invented and developed rapidly in the latter half of the last century and utilized mostly for communications and radars. After the World War II, W. C. Brown of the

United States and his colleagues extensively studied the microwave power transmission (MPT) technology. A review paper by himself[4] gives a good historical overview of the development of the MPT which stimulated and triggered the Glaser idea of the SPS (Solar Power Satellite).

Wireless power transmission (WPT) via microwave essentially utilizes the same technologies used for wireless communication. The both technologies and based on the same set of Maxwell's equations. Difference is only a viewpoint of utilization of radio waves. For the wireless communication, radio waves are used only for carrier of information. This means that the efficiency of transmission of the carrier power is not the primary issues. All needed in the telecommunication is to extract information from the radio signals. In contract, we use radio waves as carrier of energy. Therefore, we basically use a single monochromatic carrier wave for the power transmission. Therefore, efficiency is very important for the WPT system. Another difference is a power density. The WPT uses three or four orders of magnitude higher power density.

The advantages of the WPT over conventional power transmission over lines are as follows:

- It does not need any power lines connecting a power generator and the power consumers. Therefore, we have the freedom of choice of both the transmitter and receiver locations. We can even choose mobile transmitters and receivers for WPT system.
- One transmitter site can distribute power toward multiple customers simultaneously like broadcasting.
- A receiver called antenna is lighter than a commonly used battery or photovoltaic cells. Further power is available at antenna sites as long as the WPT is operating. This removes troubles of power shut down due to battery exhaustion.
- A power loss of WPT is much smaller than that of line transmission. The power loss in radio propagation is less than 1% even for a long distance transmission of several tens of thousands kilometers like used for the SSPS.

We can define three efficiencies; DC-RF conversion efficiency in MPT transmitter, RF-DC conversion efficiency in MPT receiver, and efficiency related to a power loss by beam diffusion and diffraction in propagation of microwave, respectively. Overall DC-RF-propagation-RF-DC conversion efficiency is predicted[5] over 50 %. Brown achieved 90 % efficiency for the RF-DC conversion with the single rectenna[4]. However, it should be noted that the RF-DC conversion efficiency depends on microwave density, connected load and the method of the connection of the rectenna array[6]. The efficiency related to a power loss by beam diffusion depends on size of the transmitting and receiving antenna, distance and frequency, therefore, it is easy to realize over 90 % in the present status. On the other hand, we have not yet achieved over 85 % for the DC-RF conversion with electrically accurate beam forming. In the present status, we have achieved only 60-70 % for the DC-RF conversion with microwave tubes, e.g. phase controlled magnetron (PCM)[7] or TWTA for wireless communication[8]. Note, however, the DC-RF conversion efficiency of an available manufactured magnetron is 73 % on the average and the PCM developed at Kyoto University has an efficiency of 57%. Further, we need to add extra beam control circuits, e.g. power dividers and phase shifters, with power losses to the SSPS-MPT system with the microwave tubes for higher accurate beam control. The MPT with semi-conductor amplifiers could not achieve over 50 % for the DC-RF conversion[9]. We have to develop the microwave transmitter with higher efficiency and higher accurate beam control.

The MPT can be applied for other systems than the SSPS in space. One such example is the MPT for moving targets such as fuel-free airplane, fuel-free electric vehicle (EV), moving robot in limited areas. Another possible application of the MPT is a ground-to-ground power transmission without wires toward a distant place where wired power distribution networks is either unavailable or very poorly available. The most recently proposed MPT application is "Ubiquitous Power Source" or "Wireless Power Source" being developed by Kyoto University's group[10].
We used and would like to use the 2.45 GHz or 5.8 GHz frequency band for the MPT. These bands are legally assigned to the ISM (Industrial, Scientific, Medical) use. We believe that the MPT enters in this category but we need to discuss the frequency band for the MPT.

In 1968, P. E. Glaser[12] proposed the idea to place a solar power station (SPS) in a geostationary orbit. This stimulated NASA and DOE (Department of Energy) in the US[5] and resulted in their feasibility study of the SPS in the late 1970's. The SPS research, however, was suspended under the Reagan Administration. Since then, the US research on SPS has been decreasing. However in Japan[12,13,14] ,the research, both on system studies and microwave power transmission, has been continued. In the present paper, we focus on the recent development of the MPT and SSPS systems studies since 1995. The review for the works done before 1995 is given by Matsumoto [12].

AIII-3.4 Space Solar Power System (SSPS)

The SSPS is the hugest application for MPT. In Japan, U.S.A. and Europe, many researches on the SSPS have been and are being carried out.

Figure 2 shows committee activities concerning the SSPS feasibility studies from the 1980's to 2000's. The activity had already started in 1979 when NASA/DOE report was issued. Since then the committee activities to survey the conceptual design and the feasibility of the SSPS continued intermittently up to today. Two SSPS committee activities are going on in Japan. One is organized by NASDA (National Space Development Agency of Japan) since 1998[15,16]. The NASDA has recently merged with ISAS (Institute of Space and Astronautical Science) and NAL (National Aerospace Laboratory of Japan) to create a new space agency called JAXA (Japan Aerospace Exploration Agency). The JAXA activity will be continued even after this restructuring. It consists of one main committee and 12 working groups. The committee and the working groups provide a forum to study the SSPS conceptual and technical feasibility at different levels of components of the SSPS. More than 150 scientists and engineers are joining this committee activity under the chairmanship of one (Hiroshi Matsumoto) of the present authors.

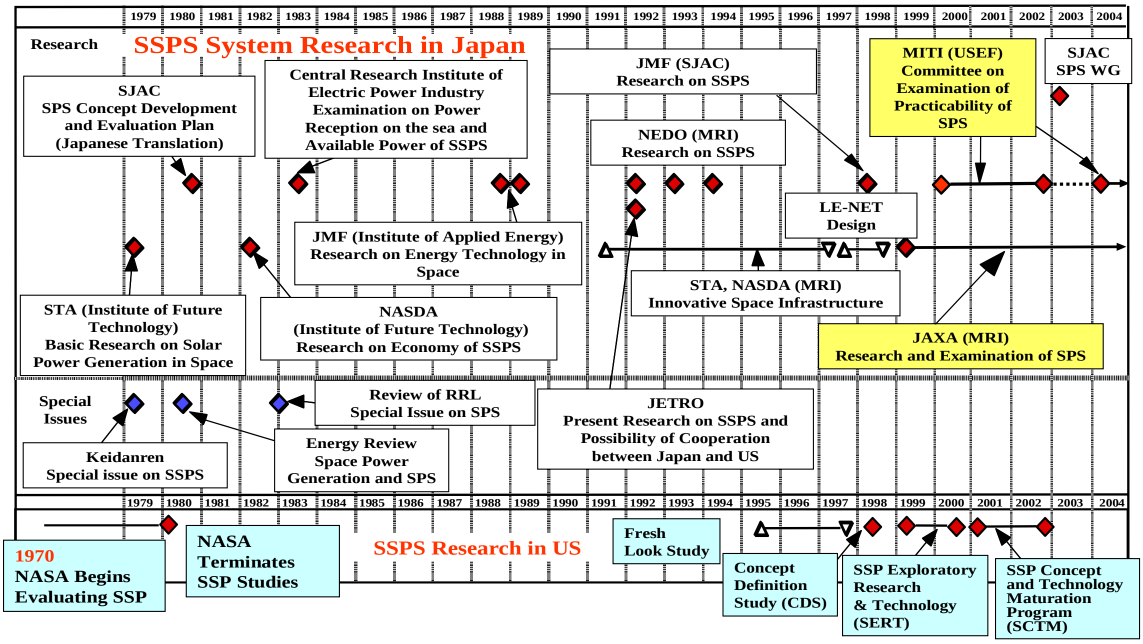
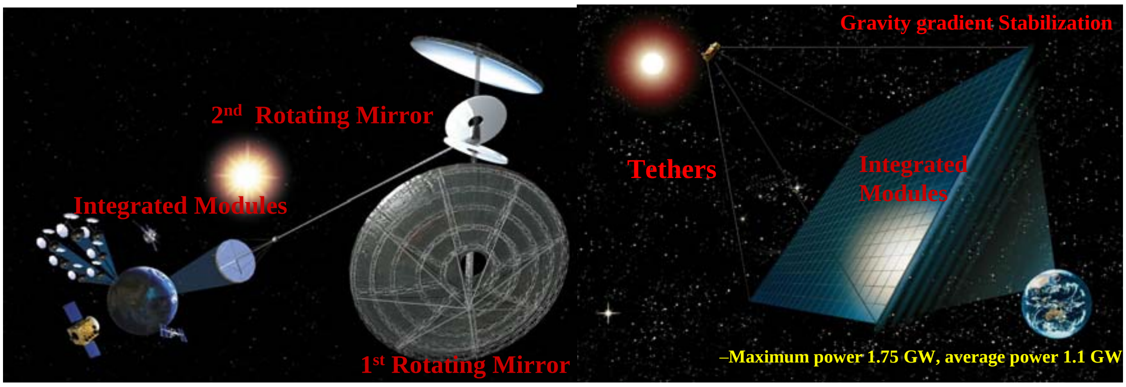


Fig 2-Conceptual and Feasibility Studies of SPS in Japan and in U.S.A .through Committee activities

An SSPS concept designed by the JAXA committee is shown in figure 3(a). Related to the proposal, MPT systems have been developed in FY2000 by a team of Kyoto University, NASDA and industrial companies. It is an integrated unit called SPRITZ (Solar Power Radio Integrated Transmitter developed in the FY of '00)[17]. This unit is composed of the solar cell panel, microwave generators, transmitting array antennas and receiving rectennas array in one package (see Fig. 4).



(a) SSPS with Solar Cells – MPT Module and Rotating mirrors designed in JAXA SSPS committee

(b) SSPS with Solar Cells – MPT Module and Tether System designed in METI SSPS committee

Fig.3 Japanese recent SSPS Model (Frequency: 5.8GHz, 1GWDC on ground)

The frequency of the microwave power beam is 5.77 GHz.

The other committee is organized by METI (Ministry of Economy, Trade and Industry) and run by USEF in 2000 – 2002[18,19]. It has one main committee and one WG. The METI SSPS design is shown in figure 3(b). In this committee, the AIA system has been developed in FY2002 as shown in Fig.2. These two committee activities will soon be merged into one.

In both designs of the SSPS, they adopt a generator-transmitter module system and omit huge DC power lines from solar cells to the microwave power generators. An artist concept of integrating the hexagonal SPRITZ-type MPT module to form a larger scale SSPS is shown in Fig. 5. The solar cells of the SSPS always have to face the sun and the transmitting antennas of the SSPS always have to confront the Earth in order to send stabilized electric powers. For solving the conflicted two motions in the module-type SSPS, they adopt two sets of rotating mirrors.

The cost of the module-type SSPS is cheaper than the separated-type SSPS like previous NASA/DOE system. The serious problem of the module-type SSPS is heat removal. There is no place for the heat reduction in the structure and we have to consider new technologies of the heat removal to realize the module-type SSPS.
Space industries in Japan, forming SJAC (Society of Japanese Aerospace Companies), have started five committees on future space missions in 2003. It contains the SSPS committee and they are planning to propose a SSPS mission in the near future to the Japanese government. A group of Japanese Congress members formed a "federation of Space Power" on February 27, 2003. Over 86 congressmen formed the Federation. Due to all these efforts, the Japanese cabinet, recently, passed its energy policy in which it stated the importance of Space Power and recommended to pursue fundamental research in this field.

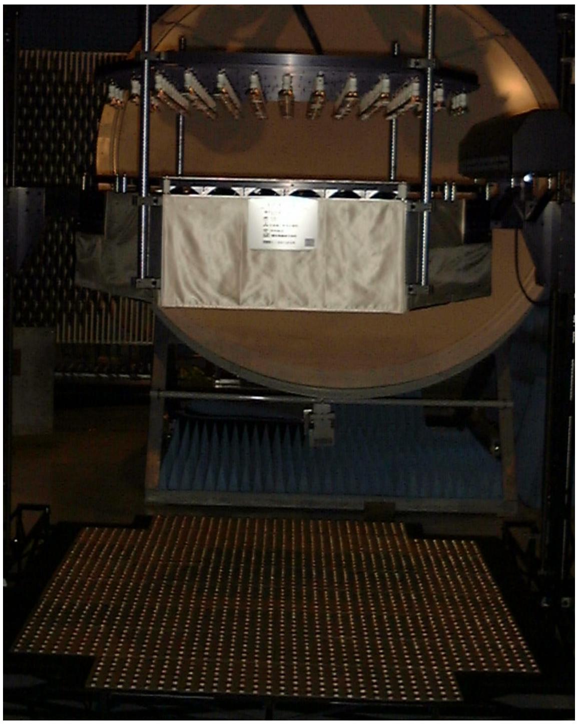


Fig.4-SPRITZ (Solar Power Radio Integrated Transmitter developed in the FY of 2000)[11]

One of the key bottleneck technologies is a launching vehicle which carries the materials of the SSPS to a geostationary orbit. The launching cost is related to the efficiency of the system, e.g. the MPT and solar cells, and to the weight of the SSPS. The cost of the SSPS and the electric power is related to the launching cost. We need 2nd or 3rd generation launching vehicles for the SSPS. The Japanese SSPS committees have set a roadmap of the launching vehicles to the SSPS. It is predicted that the R&D of the next-generation rockets (probably re-usable rockets) will lower the cost of the launching to a tolerable level in 20 years.

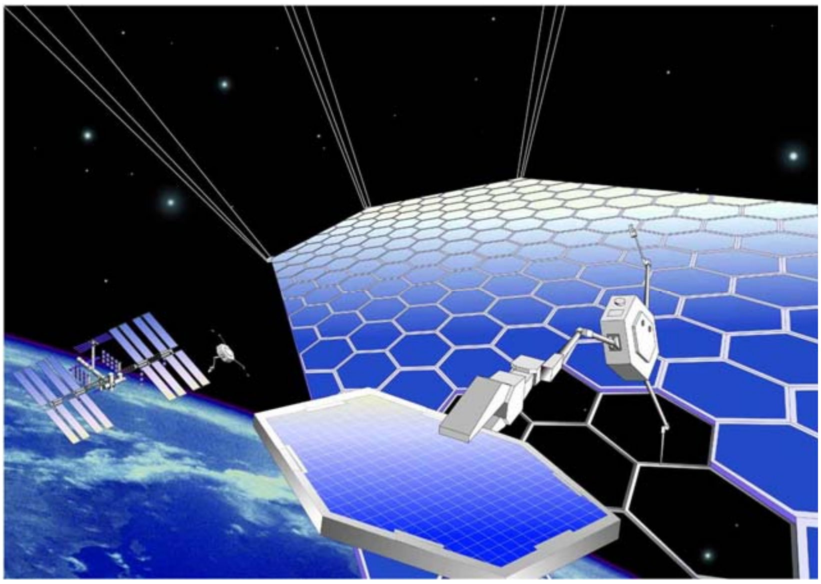


Fig. 5 An artist's concept of integrating the hexagonal SPRITZ-type MPT module to form a larger scale SSPS designed by JAXA committee

In the 1980's, activities of the SSPS research in U.S.A. have been suspended. However, "Fresh Look Study" program[20] started from 1995 for the SSPS research program. In the program, they compared all SSPS proposed before 1995 with consideration of user area. As a result, they conclude that "Sun Tower" type SSPS is economical and its structure provides easy construction and maintenance. After the Fresh Look Study program, they accelerate the SSPS research, e.g. Concept Definition Study (CDS) program (1998), SSP Exploratory Research & Technology (SERT) program (1999-2000)[21], and SSP Concept and Technology Maturation Program (SCTM)[22] (2001-2002).

ESA (European Space Agency) is also interested in the SSPS and they formed the Advanced Concepts Team (ACT) in 2003. The program is composed of three-phases. The first phase(Validation Phase) did not try to find new SSPS concepts, but focused on a comparison of space solar power plant with comparable terrestrial solutions on one hand, and on the assessment of the potential of the SSPS for space exploration and space application on the other. They organized an international conference on Solar Power from Space (SPS'04) in July 2004.

AIII-3.5 Conclusions

The MPT is the third application of radio waves next to wireless communications and remote sensing. The SSPS is a most important application of the MPT. In Japan, university researchers, company engineers, and government agency have a strong interest in the SSPS as we have a dark future unless we could solve our serious problems of energy and environmental crises. Though the core research areas set by the Committee of Science and Technology Promotion (CSTP) in the Japan Government of the research is more or less away from the space and energy program, we strongly believe the SSPS is one promising project for the sustainable humanosphere in this century. Not only the efforts in Japan but also world-side efforts towards the SSPS are currently growing, which is noteworthy. The enabling microwave and antenna technologies are to be an emerging issue for all who concerns our future.

Acknowledgement

The present review is based on efforts by all researchers for the SSPS. Special thanks go to M. Mori at JAXA and to K. Hashimoto and T. Mitani at RISH of Kyoto University.

References

[1] Tesla, N., The transmission of electric energy without wires, *The thirteenth Anniversary Number of the Electrical World and Engineer,* March 5, 1904.

[2] Tesla, N., Experiments with Alternate Current of High Potential and High Frequency, *McGraw Pub. Co.,* N.Y., 1905.

[3] Yagi, H. and S. Uda, Feasibility of Electric Power Transmission by Radio Waves, *Third Pan-Pacific academic conference,* Tokyo, 1926.

[4] Brown, W. C., The history of Power transmission by radio waves, *IEEE transaction on microwave theory and techniques,* MTT-32, pp.1230-1242, 1984.

[5] DOE and NASA, Satellite Power System; Concept Development and Evaluation Program, Reference System Report, 1979.

[6] Shinohara, N. and H. Matsumoto,"Experimental Study of Large Rectenna Array for Microwave Energy Transmission", IEEE-MTT, vol.46, No.3, 1998, pp.261-268

[7] Shinohara, N., H. Matsumoto, and K. Hashimoto, "Solar Power Station/Satellite (SPS) with Phase Controlled Magnetrons", *IEICE Trans. Electron*, vol. E86-C, no.8, 2003, pp.1550-1555

[8] Katayama, K., "Review of Performance Improvement and Development Trends of Space TWTA *(in Japanese)*", *Tech. Report of IEICE,* SPS2003-03, 2004, pp.15-22

[9] Kitazawa, S., Commercialization of the on-Board Equipments for Communications Satellites in Japan, *MWE'96 Microwave Workshop Digest [WS14-3]*, 1996, pp.387-395

[10] Shinohara, N., H. Matsumoto, T. Mitani, H. Shibata, T. Adachi, K. Okada, K. Tomita, and K. Shinoda, "Experimental Study on "Wireless Power Space"", *Technical Report of IEICE*, SPS2003-18, 2004, pp.47-53

[11] Glaser, P. E., Power from the Sun, *Science,* 162, pp.857-886, 1968.

[12] Matsumoto, H., "Microwave Power Transmission from Space and Related Nonlinear Plasma Effects", *Space and Radio Science Symposium - 75th Anniversary of URSI,* 1995, pp.155-190

[13] Matsumoto, H., "Research on Solar Power Station and Microwave Power Transmission in Japan : Review and Perspectives", *IEEE Microwave Magazine,* pp.36-45, December 2002

[14] Matsumoto, H., Wireless Power Transmission, *Handbook on Energy Technology,* ed. by K. Heinloth, Germany, 2000.

[15] Matsumoto, H. and Y. Kaya, "Japanese Trial for a Bright and Clean Energy from Space; Solar Power Station (SPS) and Microwave Power Transmission (MPT)", *Commission H special symposium on SPS, Proc. of URSI General Assembly*, Maastricht, 2002

[16] Mori, M., Y. Saito, H. Nagayama, and H. Matsumoto, "Overview of Space Energy Utilization Activities of NASDA (in Japanese)", *Proc. of 5th SPS symposium*, 2002, pp.119-124.

[17] Mori, M., H. Nagayama, T. Hanyu, and H. Matsumoto, "Summary of Studies on Space Solar Power Systems of NASDA (in Japanese)", *Proc. of 4th SPS symposium*, 2001, pp.121-126.

[18] Sasaki, S. and USEF SSPS Study Team, "Conceptual Study of SSPS Demonstration Experiment", *Proc. of Japan-US Joint Workshop on SSPS (JUSPS),* Jul. 2003, pp.156-160

[19] Kobayashi, T., "Recent USEF Studies on Space Solar Power System (SSPS) (in Japanese)", Proc. of 5th SPS symposium, 2002, pp.125-130.

[20] Mankins, J. C., "A fresh look at the concept of space solar power", *Proc.of SPS'97,* S7041, (in Montreal), 1997

[21] http://procurement.nasa.gov/cgi-bin/EPS/sol.cgi?acqid=150#Amendment 01, "SPACE SOLAR POWER (SSP) EXPLORATORY RESEARCH AND TECHNOLOGY (SERT) PROGRAM, SOL NRA8-23"

[22] http://space-power.grc.nasa.gov/ppo/sctm/

AIII-4 SOLAR THERMAL POWER PLANTS

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[1.] AIII-4.1 Concentration and thermal conversion of solar energy

Solar energy has a high energetic value since it originates from processes occurring at the sun's surface at a black-body equivalent temperature of approximately 5777 K. Because of this high exergetic value, more than 93% of the energy may be theoretically converted to mechanical work by using thermodynamic cycles[1], or to Gibbs free energy of chemicals by solarized chemical reactions[2]. According to thermodynamics and Planck´s equation, the conversion of solar heat to mechanical work or Gibbs free energy is limited by the Carnot efficiency, and therefore to achieve maximum conversion rates, the energy should be transferred to a thermal fluid or reactants at temperatures close to that of the sun.

Even though solar radiation is a source of high temperature and energy at origin, with a high radiosity of 63 $MW.m^{-2}$, sun-earth geometrical constraints lead to a dramatic dilution of flux and to irradiance available for terrestrial use only slightly higher than 1 $kW.m^{-2}$, and consequently, supply of low temperatures to the thermal fluid. It is therefore an essential requisite for solar thermal power plants and high temperature solar chemistry applications to make use of optical concentration devices that enable the thermal conversion to be carried out at high solar fluxes and with relatively low heat losses. A simplified model of a Concentrating Solar Power (CSP) plant is depicted in Figure 1.

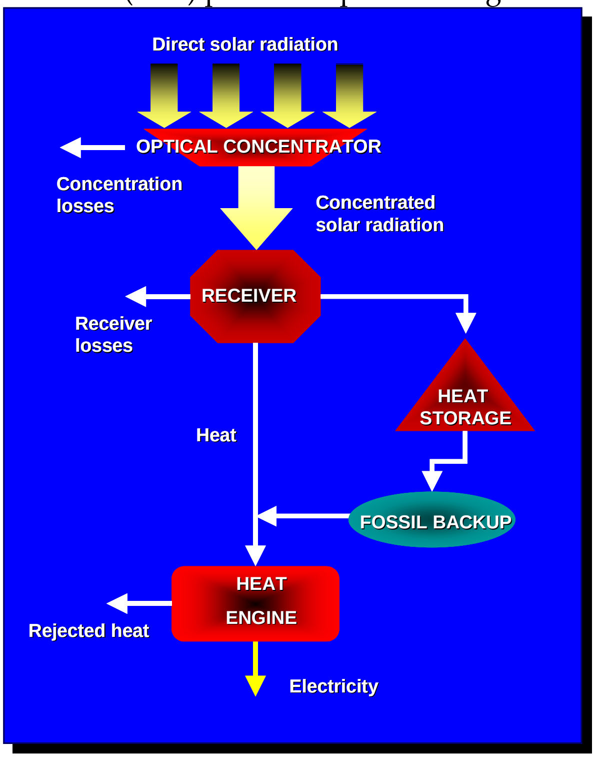

Figure 1- Flow diagram for a typical solar thermal power plant.

The optimum CSP system design combines a relatively large, efficient optical surface (e.g., a field of high-reflectivity mirrors), harvesting the incoming solar radiation and concentrating it onto a solar receiver with a small aperture area. The solar receiver is a high-absorptance and transmittance, low-reflectance radiative/ convective heat exchanger that emulates as closely as possible the performance of a radiative black-body. An ideal solar receiver would thus have negligible convection and conduction losses. In the case of a solar thermal power plant, the solar energy is transferred to a thermal fluid at an outlet temperature high enough to feed a heat engine or a turbine that produces electricity. Solar transients and irradiance fluctuations can be mitigated by using an oversized mirror field (solar multiple higher than 1) and using the excess energy to load a thermal or chemical storage system. Hybrid plants using fossil backup burners connected in series or in parallel are also possible.

The use of heat storage systems and fossil backup make CSP systems highly flexible for integration with conventional power plant design and operation and for blending the thermal output with fossil fuel, biomass and geothermal resources[3]. The use of large solar multiples with low-cost heat storage systems of up to 12 hours (equivalent at nominal power), facilitates the design of firm capacity plants supplying between 2000 and 6000 hours of operation (equivalent at full load). In addition, hybridization is possible in power booster and fuel saver modes with natural gas combined-cycles and with coal-fired Rankine plants, and may accelerate near-term deployment of projects due to improved economics and reduced overall project risk[4]. As a consequence, CSP can currently supply dispatchable power and meet peaking and intermediate loads at the lowest electricity costs of any solar grid-connected technology[5].

Additional merits of CSP may be listed as follows[6]:

Proven capabilities •e.g., 354 MW of trough plants in operation for 15 years have selectively demonstrated excellent performance, availability, a reduction in investment cost of almost 50%, and significant reductions in O&M cost.,

Modular, and •thus suitable for large central facilities in the 100's of MW down to distributed generation in the 10's of kW.

Can be rapidly deployed using entirely domestic resources and existing infrastructure.

Scale can be significant enough to impact climate change targets.

Suitable for IPP (Independent Power Producer) projects as well as turnkey projects.

Proven potential for further cost reduction, including those resulting from economies of scale, i.e. from mass production of glass, steel, etc.

AIII-4.2 CSP system experience and maturity

Solar Thermal Power Plants (STPP) with optical concentration technologies are important candidates for providing the bulk solar electricity needed within the next few decades, even though they still suffer from lack of dissemination and confidence among citizens, scientists and decision makers.

Concentrating solar power today is represented at pilot and demonstration-scale by four technologies[1]: parabolic troughs (PT), linear Fresnel reflector systems (LF), power towers or central receiver systems (CRS), and dish/engine systems (DE).

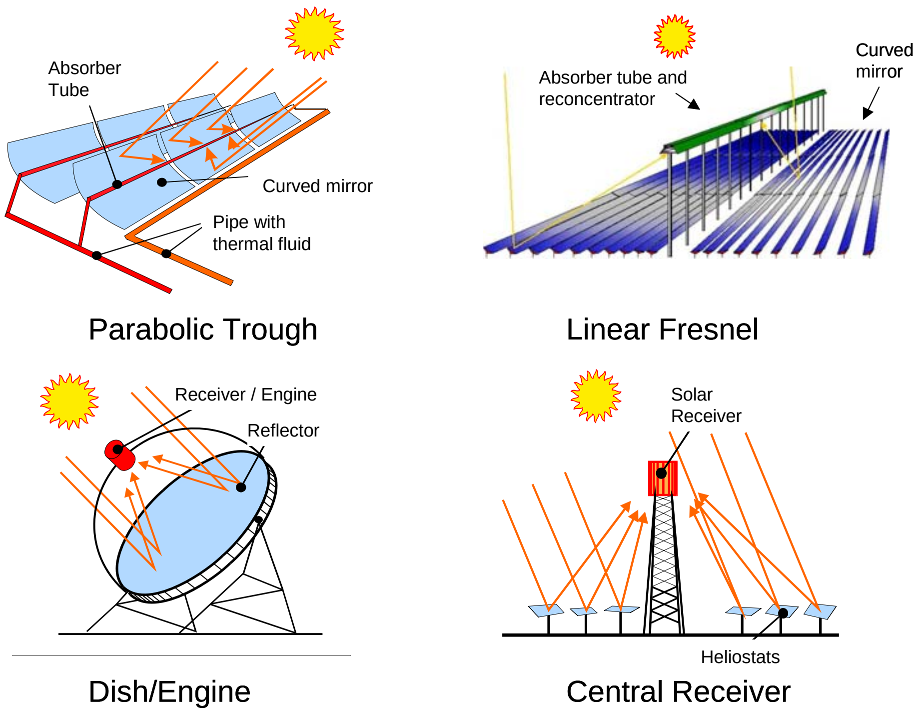

Figure 2. Schematic diagrams of the four CSP systems scaled up to pilot and demonstration sizes.

All the existing pilot plants mimic parabolic geometries with large mirror areas and work under real operating conditions. Reflective concentrators are usually selected since they offer better perspectives for scale-up. PT and LF are 2-D concentrating systems in which the incoming solar radiation is concentrated onto a focal line by one-axis tracking mirrors. They are able to concentrate the solar radiation flux 30 to 80 times, heating the thermal fluid up to 393ºC, with unit sizes of 30 to 80 MW, and therefore, they are well suited for central generation with a Rankine steam turbine/generator cycle for dispatchable markets. CRS have more complex optics, since the solar receiver is mounted on top of a tower and sunlight is concentrated by means of a large paraboloid that is discretized into a field of heliostats. The 3-D concentrator works off-axis and heliostats need two-axis tracking. Concentration factors are between 200 and 1000 and unit sizes are between 10 and 200 MW, and are therefore well suited for dispatchable markets and integration into advanced thermodynamic cycles. A wide variety of thermal fluids, like saturated steam, superheated steam, molten salts, atmospheric air or pressurized air, can be used, and temperatures vary between 300ºC and 1000ºC. Finally, DE systems are small modular units with autonomous generation of electricity by Stirling engines or Brayton mini-turbines located at the focal point. Dishes are parabolic 3D concentrators with high concentration ratios (1000-4000) and unit sizes of 5-25 kW. Their current market niche is in both distributed on-grid and remote/off-grid power applications[7].

Typical solar-to-electric conversion efficiencies and annual capacity factors, as compiled by IEA SolarPACES experts for the four technologies, are listed in the table below[5,8]. The values for parabolic troughs, by far the most mature technology, have been demonstrated commercially. Those for linear Fresnel, dish and tower systems are, in general, projections based on component and large-scale pilot plant test data and the assumption of mature development of current technology. Regarding costs, it is generally agreed that with current investment costs all STPP technologies require a public support strategy for market deployment. An independent study promoted by the World Bank[9] confirms STPP as the most economical technology for solar production of bulk electricity. However, its diagnosis finds the direct capital costs of STPP to be 2.5 to 3.5 times those of a fossil-fueled power plant and generation costs of the electricity produced 2 to 4 times higher.

Table 1. Characteristics of Concentrating Solar Power Systems[5]

System	Peak Efficiency	Annual Efficiency	Annual Capacity Factor
Trough/Linear Fresnel	21%	10 to 12% (d) 14 to 18% (p)	24% (d)
Power Tower	23%	14 to 19% (p)	25 to 70% (p)
Dish/Engine	29%	18 to 23% (p)	25% (p)
(d) = demonstrated, (p) = projected, based on pilot-scale testing. Annual Capacity Factor refers to the fraction of the year the technology can deliver solar energy at rated power.			

Every square meter of CSP field can produce up to 1200 KWh thermal energy per year or up to 500 kWh of electricity per year. That means a cumulative savings of up to 12 tons of carbon dioxide and 2.5 tons of fossil fuel per square meter of CSP system over its 25 year lifetime[10]. In spite of their promising applications and environmental benefit, to date, only parabolic troughs have operated commercially (in nine SEGS plants totaling 354 MW, built by LUZ in California in the 1980s and 1990s). The high initial investment required by early commercial plants (3000-4000 $\$.kW^{-1}$) and the restricted modularity generally motivated by the expensive thermodynamic cycle, combined with the lack of appropriate power purchase agreements and fair taxation policies, have led to a vicious circle in which the first generation of commercial grid-connected plants becomes difficult to implement without market incentives. After two decades of frozen or failed projects, approval in the past few years of specific financial incentives in Europe, the US, Australia and elsewhere, is now paving the way for the launching of the first commercial ventures.

The parabolic trough is today considered a fully mature technology, ready for deployment[11]. Early costs are expected to be in the range of 0.15-0.18 $\$.kWh^{-1}$ (and even 30% less in hybrid systems), and technological and financial risks are expected to be low. In recent years, the five plants at the Kramer Junction site (SEGS III to VII) have achieved a 30% reduction in operating and maintenance costs, a record annual plant efficiency of 14% and a daily solar-to-electric efficiency near 20%, as well as peak efficiencies up to 21.5%. Annual plant availability exceeds 98% and collector field availability is over 99%[12]. In view of this advanced state of development, several utilities are already pursuing opportunities to build plants similar to the California SEGS plants using existing technology, with various hybridization options, including integrated solar combined-cycle systems (ISCCS). Such ISCCS initiatives are now underway in four developing countries, India, Egypt, Morocco, and Mexico, with World Bank/GEF support to buy down the cost of early plants[13]. In the US, a trough system revival is beginning to take off after an agreement signed by Nevada utilities and Duke Power for a 50 MW plant, with possible expansion to 60 MW, near Boulder City, in December 2002. The system will be erected by Duke Power, using its own new DS-2 trough collector, and is to come online in 2005. The utilities will buy the power output over a 20-year contract sales period. The contracts are part of the utilities' compliance with the Nevada renewable portfolio that requires 15% renewable electricity sales by 2013, a 5% share of which must be solar-electric generation (about 60 MW). The trough plant is a one-shot response to that legal mandate[14]. In Spain, analogous legislation establishes feed-in tariff incentives in the form of a market-rate premium for electricity produced in solar-only plants with a maximum unit size of 50 MW, with target deployment of 200 MW of STPP by the year 2010. AndaSol, a first privately owned and financed commercial 50-MW project, with large 6-to-9-hour molten-salt heat storage systems, is under construction near Granada, with commissioning planned for 2006. The AndaSol project will demonstrate the innovative EURO Trough technology (a fully European trough collector) for the first time on a utility scale, using a 510,120-m^2 parabolic-trough solar field[15].

Linear Fresnel reflector systems are conceptually simple, using inexpensive, compact optics, that can produce saturated steam at 150-360ºC with less than 1 Ha.MW^{-1} land use. It is therefore a CSP technology best suited for integration with combined-cycle recovery boilers, to replace the bled steam extracted in regenerative Rankine power cycles or for saturated steam turbines. The most extensive prototype-scale experience has been the very compact designs with multi-tower aiming of the mirror slabs developed at the University of Sydney in Australia[16]. Despite their simplicity, LF systems lack scale-up experience for eventual electricity production. This situation is hopefully changing, since a first 36-MW commercial project was initiated in Australia in 2003 by the Solar Heat & Power company[17]. This proof-of-technology project is located in an existing coal-fired power plant, with the 132,500-m^2 compact LF field supplying 270°C pre-heat thermal energy to replace the extracted bled steam in the regenerative Rankine power cycle. The plant will be competitive with wind generation in Australia under current incentives (Renewable Energy Certificates Trading). Another 10-MW LF project (with possible enlargement to 50 MW), which will benefit from solar feed-in tariffs, is being pursued by Solarmundo[18] in Southern Spain, however this project is still in an early stage of definition.

Power tower technology, after a proof-of-concept stage, is today on the verge of commercialization, although less mature than the parabolic trough technology. To date, more than 10 different CRS experimental plants have been tested worldwide, generally, small demonstration systems of between 0.5 and 10 MW, and most of them operated in the 80's[19]. That experience demonstrated the technical feasibility of the CRS power plants, and their capability to operate with large heat storage systems. The most extensive operating experience has been in the European pilot projects located in Spain on the premises of the Plataforma Solar de Almería, and in the US at the 10-MW Solar One and Solar Two facilities located in California. Solar One is the only one that accumulated grid-connected operating experience, which lasted for three years. The system's high reliability provided 96% availability during sunlight hours, but with an unexpectedly low annual efficiency (only 7% heat-to-electricity), and intermittent turbine operation caused by cloud transients. Continuous technological improvement now places current predictions for CRS design-point efficiency at 23% and annual at 20%[8], but a first generation of commercial demonstration plants still remains an essential requisite to validate the technology under real operating and market conditions. The three most promising power tower technologies that are expected to lead to commercial plants in the next few years are: 1) molten salt technology, 2) open or closed loop volumetric air technologies, and 3) saturated steam technology[19]. The technology favored by US industry is based on solar-only power plants with molten nitrate salts as the working fluid and large thermal storage capacity, with most recent effort focused on the definition and engineering of a "breakthrough-type" 100-MW plant for South Africa. The use of volumetric receivers, both with closed air loops for efficient integration into gas turbine cycles and open air for intermediate storage and/or hybridization solutions have been promoted in Europe and Israel with pilot projects such as SOLGATE, SOLAIR and Consolar, but a commercial project has not yet been undertaken. Finally, a more conservative approach, with solar saturated-steam receivers for cogeneration and power production, is used in the SOLGAS and PS10 initiatives, both in Southern Spain. PS10 is the only commercial solar tower project started. The project, led by Solúcar Energía, consists of an 11-MW system, with the solar receiver producing 40 bar/250ºC saturated steam. To provide for cloud transients, the plant will have a 15-MWh-capacity (50 minutes at 50% load) saturated steam thermal storage system.

Figure 3. Detail of CIEMAT's 7-MWth CESA-I tower system and its 12000-m^2 heliostat field, located in Almeria (Southern Spain).

Dish/engine systems are absolutely modular and ideal for unit powers between 5 and 25 KW, but are strongly challenged by PV systems which compete for the same market niche. Two decades ago, dish/Stirling systems had already demonstrated their high conversion efficiency, concentration of more than 3000 suns, and operating temperatures of 750°C at annual efficiencies of 23% and 29% peak[21]. Unfortunately, DE have not yet surpassed the proof-of-reliability operation phase. Only a limited number of prototypes have been tested worldwide, and annual availability above 90% still remains a key challenge. Given the fact that autonomous operation and off-grid markets are the first priorities of this technology, more long-endurance test references must be accumulated. DE technology investment costs, which are twice as high as those of parabolic troughs[22], would have to be dramatically reduced by mass-production of specific components, like the engine and the concentrator. DE system industries and initiatives are basically confined to the US and Europe[23]. In Europe, Schlaich Bergermann und Partner have extensively tested several 9-10-kW systems (based on a structural dish and the Solo 161 kinematic Stirling engine) at the Plataforma Solar de Almería, and follow-up activities based on the EuroDish design are being pursued with a European Consortium involving SBP, Inabensa, CIEMAT, DLR and others. In the US, Science Applications International Corp. and STM Corp, with the sponsorship of DOE, are testing 25-

kW systems based on the STM 4-120 Gen III engine, while Stirling Energy Systems continues development of the 25-kW MDAC system originally tested in the 1980s for potential use in a 1-MW plant in Nevada. An SES dish-Stirling system is also under testing in South Africa. WGAssociates and Sandia National Laboratories have demonstrated a 10-kW remote power system in an advanced dish design with the Solo Stirling engine. These systems should be commercially available within a few years, once availability is demonstrated and market opportunities develop. Initial costs will be higher than troughs and power towers, although these systems, because of their modular nature, are targeted toward much higher-value markets.

AIII-4.3 The markets

World energy outlooks, issued by different international organizations and government departments, such as the WEC (World Energy Council), the IEA (International Energy Agency), the US-DOE (US Department of Energy) and the EC (European Commission) anticipate steady renewables growth for the period 2000-2030. In spite of this development and because of very low initial levels, electricity from renewable sources is not expected to exceed 3% of world total electricity production in 2030 (16% if large hydro and geothermal plants are included). This is, for example, the EC WETO (World Energy, Technology and Climate Policy Outlook) prediction published in 2003[24]. Solar technologies have a very small role to play according to these general studies and their share will be very limited. The poor dissemination of STPP and CSP technologies, and the absence of commercial references lead to the real fact that most of these Energy Outlooks do not consider solar thermal power a credible option for the next two decades, and simply obviate it. It is, therefore, in more renewable-oriented studies and technical roadmaps elaborated in close cooperation with solar engineers where detailed information about potential deployment of CSP plants can be found. Different studies sponsored by EPRI, the World Bank[9], ISES[14], IEA-SolarPACES[5], EUREC[22], SunLab[25], UNDP[26] or IEA [27]consider the implementation of 2 – 8 GW by the year 2010 highly feasible, rising to between 20 –45 GW by 2020[6]. The United Nations Development Programme (UNDP), United Nations Department of Economic and Social Affairs (UNDESA), and World Energy Council (WEC) published the World Energy Assessment (WEA) in 2000. WEA´s outlook gives forecasts beyond 2020, for a growth rate of 20–25 percent after 2010, and an average 15 percent a year after 2020, after which the result predicted would be 800–1,200 GW of CSP electricity by 2050. The Cost Reduction Study for Solar Thermal Power Plants, prepared for the World Bank in early 1999 concludes that the large potential market of CSP could reach an annual installation rate of 2,000 megawatts of electricity[9] between 2015 and 2020.

The need to find global joint strategies for removal of the non-technological barriers impeding Concentrating Solar Power and to devise a bold and effective plan to greatly expand the international market for it, in an accelerated time frame, have been the subject of two international executive conferences (June 2002 in Berlin, Germany, and October 2003 in Palm Spring, USA). The result of those conferences, attended by senior executives from the energy, financial and policy sectors of many countries, was the definition and launching of the Global Market Initiative (GMI), a coordinated global market initiative for .concentrating solar power (CSP) aimed at erecting 5,000 MW of large-scale CSP power projects in prime areas around the world on an aggressive time scale[10]

CSP technologies are capable of meeting the requirements of two major electric power markets: large-scale dispatchable markets comprised of grid-connected peaking and base-load power, and rapidly expanding distributed markets including both on-grid and remote/off-grid applications. Dispatchable markets, where power must be produced on demand, can be served with large trough and tower plants using storage and hybridization. The CSP technology appropriate for distributed applications is the dish/engine system, however, its market entry requires a drop in the price of electricity to below 12¢ .kWh^{-1} (industrialized countries) and below 30¢.kWh^{-1} (developing countries); it requires capital costs of $1-2/W (IC) and $4/W (DC) and about 100 MW installed capacity. For PT/CRS market entry, the electricity price would have to drop below 8¢.kWh^{-1} (low enough to compete in large-scale peaking and green markets), capital costs would have to be 2-4 times lower and 1,000 MW installed capacity would be required[6]

The reduction in electricity production costs should be a consequence not only of mass production, but also of up-scaling and R&D[25]. According to the most recent parabolic-trough analyses conducted at SunLab, the cost reduction projected for 2020 will be 37% from plant scale-up, 42% from technology development and 21% from mass production[28]. This means that GMI and other market penetration strategies must be combined with continuous R&D, since almost half of the expected reduction in the near future will be from technology improvements.

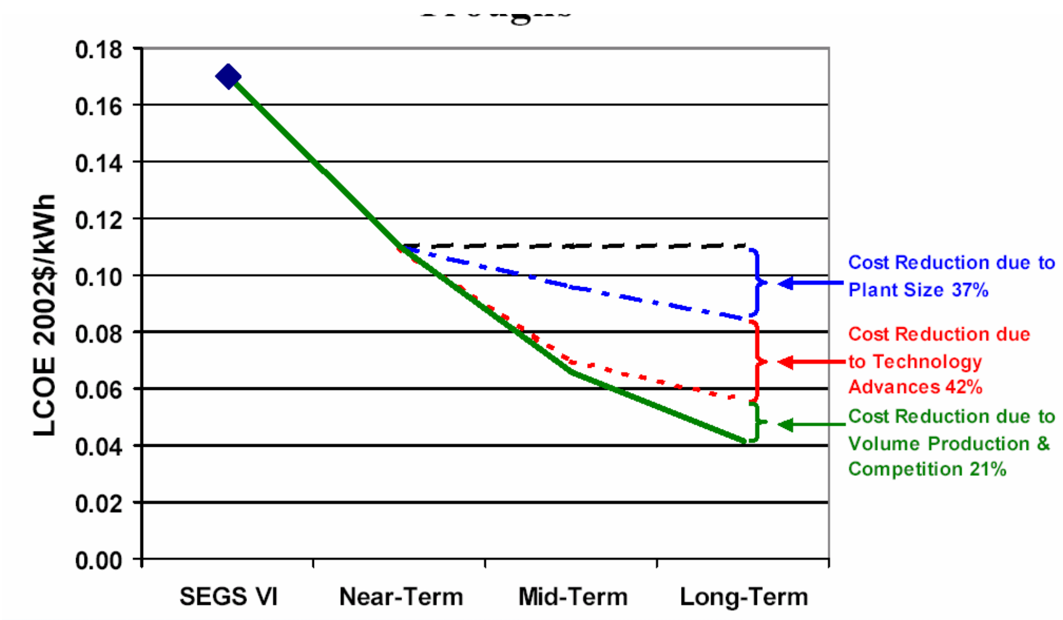

Figure 4. Impact of plant size, technology advances and production volume on levelized cost of electricity produced by parabolic troughs as predicted by SunLab in the US

AIII-4.4 Research and developments needs

In spite of the relevance of R&D for cost reduction of CSP, the fact is that the number of scientists and engineers involved in technology development is still relatively small. The only collaborative framework for stable cooperation in STPP development is the SolarPACES community (Solar Power and Chemical Energy Systems), an IEA implementing agreement which has been the hub of task-sharing activities from 14 countries since 1977. Some of the key general topics on medium to long-term R&D proposed by the IEA-SolarPACES community are[29]:

Build confidence in the technology through:
- pilot applications based on proven technologies;
- high reliability of unattended operation;
- increased system efficiency through higher temperatures;
- hybrid (solar/fossil fuel) plants with small solar share;

Reduce costs through:
- improved designs, materials, components, subsystems and processes;
- exploitation of economies of scale.
-
- Increase solar share through:
- suitable process design;
- integration of storage.

In all cases, R&D is multidisciplinary, involving optics, materials science, heat transfer, control, instrumentation and measurement techniques, energy engineering, thermal storage, etc.[5], [25]

AIII-4.4.1 Trough and Linear Fresnel Power Plants

To further reduce costs and increase reliability in next generation PT and LF technology, the following are expected:
- improvements in the collector field as a result of lighter and lower-cost structural designs through further aerodynamic analyses and advanced structural composite materials;
- development of front surface mirrors with solar-weighted reflectivity of about 95%;
- development of high-absorptance coatings for tube receivers (96% and higher) able to work efficiently at over 500ºC.
- development of medium temperature thermal energy storage systems (PCM, molten salts, concrete) suitable for solar-only systems;
- Continued improvement in overall system O&M, including mirror cleaning, integral automation and largely unattended control;
- system cost reductions and efficiency improvements from substituting water for synthetic oil as the heat-transfer fluid (Direct Steam Generation technology);
- development of advanced solar/fossil hybrid designs, especially coupled with combined-cycle power plants;
- Development of innovative methods of concentrating solar energy in linear receivers, for example, the Compact Linear Fresnel Reflector in Australia, which employs nearly flat mirrors located very close to the ground.

In Europe, these improvements are being implemented through ongoing research activities such as the INDITEP Direct Solar Steam project, which is preparing this technology for a first 5-MWe pilot plant, the DISSTOR heat storage project that focuses on developing specific heat storage for direct steam generation plants, and the development of a new European trough collector in the EUROTROUGH project. Those German/Spanish developments are being tested at the Plataforma Solar de Almería in Southern Spain. All the R&D activities in the USA are integrated in the US-Trough program funded by the DOE, including development of new trough collectors like the IST and DS2; development and testing of efficient absorbers such as the new Solel UVAC receiver that has demonstrated a 20% increase in thermal performance over SEGS VI, and development of new heat storage systems based on organic salts. In

Australia, advanced concepts to improve the LF technology are being pursued by the University of Sydney.

AIII-4.4.2 Power Tower Plants

Power tower R&D in the United States, Europe, and Israel is concentrated in the two most relevant subsystems with regard to costs: heliostat field and solar receiver. The following improvements are expected:

- Improvements in the heliostat field as a result of better optical properties, lower cost structures, and better control. Improvements in materials should be analogous to those for trough collectors. In general terms, optical performance and durability of existing heliostats is acceptable (95% availability and beam quality below 2.5 mrad), therefore R&D resources should focus basically on cost reduction.
- New heliostat design activities include large-area heliostats, measuring 90 to 150-m^2 each, independently developed by Inabensa (Spain) and Advanced Thermal Systems (USA) and offering installed costs of less than \$150/m^2 for large series. Further developments should involve advanced mechanical drives.
- More intelligent and autonomous heliostats using wireless communications and PV power supply are being developed and tested by CIEMAT in Spain. Autonomous heliostats may have a significant impact in cost reduction since cabling and trenching is avoided in large fields.
- Development of advanced air-cooled volumetric receivers using both wire-mesh absorbers and ceramic monoliths is the subject of various German/Spanish/Israeli projects. A ceramic receiver producing atmospheric air heated up to 1000ºC is being tested at the Plataforma Solar de Almería within. Pressurized volumetric receivers including a front quartz window producing air at 1000ºC and 6 bar, are being tested for integration with solarized gas turbines at the PSA and in Israel. Volumetric receivers still need further development for scale-up, materials durability and thermal efficiency.
- Heat storage is another key issue for CRS development. The new developments in air-cooled receivers have led to the development of advanced thermocline storage systems making use of packed-bed ceramic materials. This system has shown excellent performance for small units of a few MWh but pressure losses and design restrictions appear when size is increased. First commercial plants will need an improved storage concept to scale up the design. R&D should focus on new concepts of air/sand systems with improved heat transfer to the steam generator. Similar improvements are expected for early commercial projects based on molten salt storage, where the existing two-tank design may be simplified with new concepts introducing single-tank thermocline systems.
- Finally, more distributed control architectures, system integration and hybridization in high-efficiency electricity production schemes should be developed as already mentioned for trough systems.
- Development of volumetric receivers in Europe is basically in EC-funded projects like SOLAIR and SOLGATE, in which atmospheric and pressurized modules have been tested. Developments in Israel are coordinated by the CONSOLAR consortium. Molten-salt R&D received an important boost during the SOLAR TWO project in the US. There are currently two projects, one in Spain (SOLAR TRES) and one in South Africa (SOLAR 100) for commercial implementation of this technology. Other components, like heliostats, storage and control, are under development in several national R&D projects in Germany, Spain, Israel, Australia and the US.

AIII-4.4.3 Dish/Engine Power Plants

Several dish/engine prototypes have operated successfully during the last 10 years in the US and Europe, but there is no large-scale deployment yet. The use of dishes for stand-alone or grid-support installations will reach near-term markets as costs drop to less than 12¢.kWh^{-1}. This lower cost can be achieved through:

improvements in mirrors and support structures, improvements in hybrid heat-pipe and volumetric receivers coupled to Stirling and Brayton engines, and development of control systems for fully automatic operation; and

improvements in system integration by reduction of parasitic loads, optimization of startup procedures, better control strategies, and hybrid Stirling-Brayton operation.

AIII-4.5 Conclusions

Solar Thermal Power Plants are excellent candidates for supply of a significant share of solar bulk electricity by the year 2020. Their strong point is their flexibility for adapting to both dispatchable and distributed markets. A near-term target of 5000 MW of grid-connected systems is considered feasible according to the Global Market Initiative (GMI) strategy, which will significantly influence the competitiveness of STPP technologies. The portfolio of concentrating solar power technologies includes mature technologies, like the market-ready parabolic troughs, technologies like solar towers and linear Fresnel systems, which are ready to start up in early 10 to 30-MW commercial/demonstration plants, and finally dish-engine systems, which have high conversion efficiencies, but have still only been tested in a few 5 to 25-kW prototypes.

Ten years from now, STPP may already have reduced production costs to ranges competitive with intermediate-load fossil power plants. An important portion of this reduction (up to 42%) will be obtained by R&D and technology advances in materials and components, efficient integration schemes with thermodynamic cycles, highly automated control and low-cost heat storage systems.

References

[1] Winter C.J., Sizmann R.L., Vant-Hull L.L. (Eds) (1991), "Solar Power Plants", Springer-Verlag, Berlin, ISBN 3-540-18897-5.

[2] Kodama T. (2003), “High-temperature solar chemistry for converting solar heat to chemical fuels”, Progress in Energy and Combustion Science 29, 567–597.

[3] Mancini, T., G.J. Kolb, and M. Prairie, (1997),“Solar Thermal Power”, Advances in Solar Energy: An Annual Review of Research and Development, Vol. 11, edited by Karl W. Boer, American Solar Energy Society, Boulder, CO,USA. ISBN 0-89553-254-9.

[4] Kolb G.J. (1998). Economic evaluation of solar-only and hybrid power towers using molten-salt technology, Solar Energy. 62, 51-61.

[5] Tyner C.E., Kolb G.J., Geyer M., Romero M. (2000), “Concentrating solar power in 2001- An IEA/SolarPACES Summary of Status and Future Prospects”, Edited by IEA-SolarPACES. May be downloaded at www.solarpaces.org.

[6] Morse F.H. (2000), “The Commercial Path Forward for Concentrating Solar Power Technologies: A Review of Existing Treatments of Current and Future Markets,” Morse Associates, Inc., by contract of Sandia National Labs. and DOE (USA). Washington D.C., December 13, 2000,

[7] Becker M., Meinecke W., Geyer M., Trieb F., Blanco M., Romero M., Ferriere A. (2002), Solar Thermal Power Plants, in: The future for Renewable Energy 2: Prospects and Directions, Eurec Agency, James&James Science Publishers Ltd., London, UK. pp. 115-137. ISBN: 1-902916-31-X

[8] DeMeo E.A., Galdo J.F. (1997), "Renewable Energy Technology Characterizations", TR-109496 Topical Report, December 1997, U.S. DOE-Washington and EPRI, Palo Alto, California.

[9] Enermodal Engineering Ltd. (1999). "Cost Reduction Study for Solar Thermal Power Plants. Final Report". Prepared by Enermodal Engineering Ltd. in association with Marbek Resource Consultants Ltd., by contract of World Bank/GEF, Washington D.C., May 5, 1999.

[10] Geyer M. (2002), "Panel 1 Briefing Material on Status of Major Project Opportunities. The Current Situation, Issues, Barriers and Planned Solutions". International Executive Conference on Expanding the Market for Concentrating Solar Power (CSP) – Moving Opportunities into Projects; 19 – 20 June 2002; Berlin, Germany.

[11] Price H., Luepfert E., Kearney D., Zarza E., Cohen G., Gee R., Mahoney R. (2002), "Advances in Parabolic Trough Solar Power Technology", Int. J. Solar Energy Eng., Vol. 124, pp. 109-125.

[12] Cohen G.E., Kearney D.W., Kolb G.J. (1999). "Final Report on the Operation and Maintenance Improvement Program for Concentrating Solar Power Plants," SAND99-1290, Sandia National Laboratories, Printed June 1999.

[13] Geyer M., Romero M., Steinfeld A., Quaschning V. (2003). "International Energy Agency – Solar Power and Chemical Energy Systems. Annual Report 2002". Ed. DLR. Printed March 2003. May be downloaded at www.solarpaces.org.

[14] Aitken D.W. (2003), "White Paper: Transitioning to a Renewable Energy Future". International Solar Energy Society-ISES, Freiburg, Germany.

[15] Aringhoff R., Geyer, M., Herrmann, U., Kistner, R., Nava, P., Osuna, R. (2002). "AndaSol-50 MW Solar Plants with 9 hour storage for Southern Spain". Proc. 11th SolarPACES International Symposium on Concentrated Solar Power and Chemical Energy Technologies. September 4-6, 2002. Zurich, Switzerland. Ed. A. Steinfeld. pp. 37-42. ISBN: 3-9521409-3-7.

[16] Mills D.R , Morrison G.L. (2000). "Compact linear Fresnel reflector solar thermal powerplants". Solar Energy 68, 263-283,

[17] Hu E.J., Mills D.R, Morrison G.L., le Lievre P. (2003), "Solar Power Boosting of Fossil Fuelled Power Plants". Proceedings ISES Solar World Congress 2003, June 14-19 2003, Göteborg, Sweden, Ed. by ISES-International Solar Energy Society and Solar Energy Association of Sweden. ISBN 91-631-4740-8.

[18] Sureda M., de Lalaing J. (2002). "The Solarmundo Project". Proceedings of the IEA/SolarPACES Tasks Meetings. Interlaken (Switzerland), September 9-10, 2002. Eds. M. Romero, A. Steinfeld, V. Quaschning. Pub. CIEMAT. ISBN 84-7834-432-2.

[19] Romero M., Buck R., Pacheco J.E. (2002), "An Update on Solar Central Receiver Systems, Projects, and Tech-nologies.", Int. J. Solar Energy Eng., Vol. 124, pp. 98-108.

[20] Radosevich L.G., Skinrood A.C.(1989), "The power production operation of Solar One, the 10 MWe solar thermal central receiver pilot plant", J. Solar Energy Engineering, 111, 144-151.

[21] Stine W., Diver R.B (1994), "A Compendium of Solar Dish/Stirling Technology", report SAND93-7026; Sandia National Laboratories, Albuquerque, New Mexico.

[22] Becker M., Meinecke W., Geyer M., Trieb F., Blanco M., Romero M., Ferriere A. (2002), "Solar Thermal Power Plants". Libro: "The future for Renewable Energy 2: Prospects and Directions". Eurec Agency. Pub. James&James Science Publishers Ltd., London, UK. pp. 115-137. ISBN: 1-902916-31-X

[23] Mancini T., Heller P., Butler B., Osborn B., Schiel W., Goldberg V., Buck R., Diver R., Andraka C., Moreno J. (2003), "Dish-Stirling Systems: An Overview of Development and Status", Int. J. Solar Energy Eng., Vol. 125, pp. 135-151.

[24] European Commission (2003). "World energy, technology and climate policy outlook 2030-WETO ".Directorate-General for Research; Energy. EUR 20366. Luxembourg: Office for Official Publications of the European Communities, 2003. ISBN 92-894-4186-0.

[25] Sargent & Lundy (2003). "Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts". National Renewable Energy Lab. Report: NREL/SR-550-34440. October 2003. Golden (Colorado), USA.

[26] Turkenburg W.C.(2000). "Renewable Energy Technologies". Chapter 7 in: "World Energy Assessment". United Nations Development Programme. New York. pp 219-272. ISBN: 92-1-126126-0

[27] IEA (2003), "Renewables for power generation. Status and prospects". IEA Publications, Paris (France). 2003 Edition. ISBN : 92-64-01918-9

[28] Jones S. (2003). "US Trough and Tower Systems". Proceedings of SolarPACES Tasks Meetings, Göteborg, Sweden, June 17, 2003. Eds: M Romero, A. Steinfeld and V. Quaschning. Pub. CIEMAT, Madrid, Spain. ISBN: 84-7834-455-1.

[29] IEA (2000). "Developing a New Generation of Sustainable Energy Technologies - Long-term R&D Needs". A Report on a Workshop of the Renewable Energy Working Party (REWP) of the International Energy Agency (IEA).

AIII-5 ENERGY FROM BIOMASS

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OVERVIEW OF BIOMASS ENERGY PROCESSES FROM PRIMARY RESOURCE TO END USE

FORM OF ENERGY TO USERS	BIOMASS PRIMARY SOURCE	PROCESSES
Liquid Fuels		
Ethanol	Sugarcane	Fermentation-distillation
Ethanol	Cassava and corn	Fermentation-distillation
Biodiesel	Palm oil, castor oil, soybean oil	Transesterification
Methanol	Sugarcane bagasse, rice straw, sugarcane waste	Gasification
Bio-oil	Sugarcane bagasse, rice straw, sugarcane waste and wood	Fast Pyrolysis
Ethanol	Sugarcane bagasse and trash, switchgrass, and agro-forestry residues	Hydrolysis
Gas Fuels		
Biogas (methane)	Landfill waste – Urban Solid Waste	Anaerobic fermentation
Hydrogen	Biomass	Ethanol reform
Electricity		
Electricity	Biomass	Gasification, combustion
Electricity	Sugarcane bagasse and trash	Co-generation
Process Heat		
Charcoal	Wood	Carbonization
Heat	Biomass (wood)	Direct combustion

AIII-5. 1 Introduction

Many of the solid, liquid, and gaseous biomass fuels that will be discussed in this section are presently not competitive with the fossil fuels they are expected to replace. A glorious exception is ethanol from sugarcane that may be produced at approximately half the current average cost of production of gasoline. This is no miracle but the result of significant effort on research and development during a quarter of a century. Figure 1 shows the learning curve for ethanol in Southeastern Brazil. This spectacular result may induce hope that the same may be expected for fuels from biomass materials. And this is possibly true for several options considered here. However, it should be understood that what happened to ethanol from sugarcane only occurred because of two essential factors. First, there was a permanent demand for improvement and a clear business opportunity. Second, a large research center supported by the private sector, acting in the many production phases, was established. Genetic varieties were developed simultaneously with harvesting management techniques in parallel to process development, etc. Chemists, biologists, mechanical, agricultural, and electrical engineers worked together with one single objective in mind; the increase in productivity. At a moment, there were more than one thousand employees in this Institution. There is no doubt that with an equivalent effort and similar market conditions the same gains that were obtained for ethanol from sugarcane can be achieved for other biomass fuels.

A good candidate is cassava, mainly because of its capacity to stand low quality soils and adverse climate, becoming, in such cases, a better choice than sugarcane. Another is switchgrass, due to its high yield.

We may also expect that soybean and other cultures to become competitive for biodiesel production. Not only because there is room for improvement but also because petroleum products will most probably have their prices increased in the near future.

Other areas in which significant efforts in research and development will probably be fruitful are the many possible routes for gasification of biomass. It is surprising that, some 15 or 20 years after its initial conception, such a promising technology as the BIG-GT has not been tested effectively. Gasification of biomass is a wide field of experimentation and should have been treated the same way as ethanol from sugarcane.

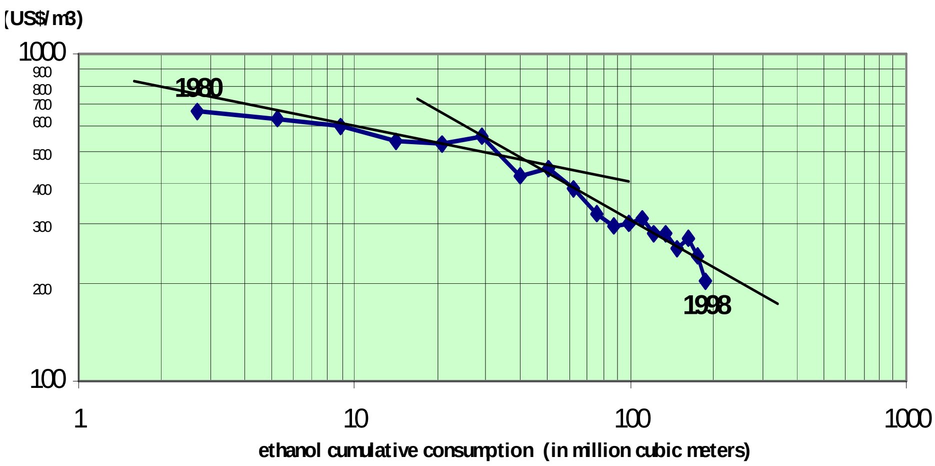

Figure 1 - Ethanol cost "learning curve" (GOLDENBERG, 2004)

We must, however, bear in mind the inherent low efficiency of photosynthesis. With a theoretical limit of 4.5% and a real value that will not surpass 1%, biomass will never entirely replace fossil fuels. Other forms of collecting solar energy sooner or latter will overcome biomass. Photovoltaic cells are already at least 10 times more efficient than biomass, though much more expensive. However, so far, we have not considered the social cost of the land area where to harvest solar energy, but it may soon become an important decision factor. Nevertheless, biomass is certainly an important choice for a transition from an economy based on fossil fuels and the next, whatever it will be.

We can clearly identify research necessities in chemistry, genetics, molecular biology, mechanical and electrical engineering, logistics, etc. Physics may have an important role in nanoscience applications. Better understanding of catalytic processes, catalytic materials, dynamics of chemical reactions that will come with nanosciences, will certainly contribute to the basic understanding of biomass processing.

LIQUID FUEL

AIII-5. 2 Ethanol

AIII-5.2. 1 AIII-5.2.1 Introduction

The use of ethanol as motor vehicle fuel has been subject to many tests during most of the 20th century. During the 1930s, the Brazilian government mandated the use of an ethanol-blended gasoline, composed of 5 percent ethanol with 95 percent gasoline. The directive was first aimed at imported gasoline, and later extended to all gasoline used in the country. It was not until the last quarter of the 20th century that fuel ethanol use programs were implemented at national scales both in Brazil and the USA. Brazil used its experience in producing ethanol from *molasses*[11] and selected the sugarcane as the raw material for large-scale fuel production.

The United States used corn because it is produced in large scale as the basic raw material for its large-scale ethanol production. The USA opted for anhydrous ethanol, while Brazil opted to produce two types of ethanol fuel: (1) anhydrous (99.5° GL), which was to be blended with gasoline; and (2) hydrous (95.5°GL), which was to be used in modified engines using 100% neat ethanol, which started to be produced in 1978. During 2003, production of ethanol reached 11.2 million m^3 in the USA and 14.1 million m^3 in Brazil, representing 43.3 and 54.2 million bOE, respectively. For 2010, these figures are expected to increase to 16.3 million m^3 (62.6 million bOE) in the USA and to 19.9 million m^3 (76.8 million bOE) in Brazil.

This section discusses the production of ethanol from sugarcane in Brazil, highlighting the driving forces, and technology challenges/developments that transformed a traditional food-producing agricultural industry into the most successful and comprehensive bio-energy program in the world.

AIII-5.2. 2 AIII-5.2.2 General background

Key world producers are shown in Table 1.1, which indicates that Brazil and the USA together were responsible for more than half of the world total production. This percentage has increased to 66% in 2003, corresponding to a combined Brazilian-American net production of 25 million m^3 (96.5 million bOE)[12].

11 Thick dark syrup produced by boiling down juice from sugarcane, especially during sugar refining.

12 **bOE: barrel of oil equivalent**

*Table 5.2.1. World ethanol production, 1999 - 2003 (Billion liters)**

Country/Region	**2003**	**2002**	**2001**	**2000**	**1999**
Europe	4.27	4.08	4.03	3.56	3.51
- EU-15	2.37	2.22	2.11	2.07	2.00
Americas	26.23	23.26	20.68	19.26	20.95
- Brazil	14.07	12.62	11.50	10.61	12.98
- USA	11.18	9.60	8.11	7.60	7.00
Asia	6.65	6.23	6.05	5.90	6.05
Oceania	0.16	0.16	0.18	0.15	0.16
Africa	0.59	0.58	0.55	0.54	0.53
- South Africa	0.40	0.40	0.40	0.40	0.40
World Total	38.3	34.71	31.89	29.81	31.60

* Approximate Figures
Source: LICHTS, F.O.

Brazil and India use *sugarcane* as their key and strategic raw material, while the USA and China essentially use corn. EU relatively small production is based primarily on surpluses of wine distillation, wheat and sugar beet.

Nearly 60% of the world ethanol production was used as fuel. This share has been increasing due to the implementation of bio-fuel programs in several countries, including India, Thailand, Colombia, Mexico, China, and Australia. Other countries, like Japan, Korea, and Sweden, although not planning to produce the bio-fuel themselves, are paving the way to the systematic use of ethanol. Many EU countries are also seeking to use and, to some extent, produce ethanol. A major driving force in the EU is the Directive on the Promotion of the Use of Biofuels for Transport (COM, 2001 pp. 547) aimed at facilitating their introduction. The aim is to replace 2% of fossil fuels in transport with biofuels by 2005 and 6% by 2010. The Directive recommends that Member States set their own national targets and implement measures to achieve them. However, depending on progress in the adoption of alternative fuels and following a review, possibly in 2007, the EU may consider "mandatory objectives if acceptable to all Member States" (for further information: www.eufores.org).

The forces pushing renewable fuel alternatives vary from country to country. However, there are some common features:

- Environmental: concern with clean air is a social and political priority throughout the world;
- Energy security: increasing dependency on imported energy supply is also a general concern, particularly in the EU and USA;
- Social and economic pressures: many countries regard alternative fuels, not only as environmentally clean, but also as an effective tool for socio-economic development, particularly in rural areas.

For all these reasons many governments currently support liquid biofuel programs through legislation and tax incentives, as it is the case in many EU member countries. Support for a particular fuel is dictated by the specific circumstances of a country or region.

In Brazil, the legal and institutional framework for the ethanol fuel program was set by the creation of the National Ethanol Program (ProAlcool) in November of 1975, in the aftermath of the 1973 Arab oil embargo. The ProAlcool included the mandate of blended fuel (20% ethanol and 80% gasoline) and created the necessary conditions for the production of *neat ethanol cars* (100% ethanol-fuelled engines), which started to be produced in 1978. Several legislative measurers have been passed within the scope of this Program and it has been kept alive until today. The USA waited a while longer to react in the direction of alternative fuels, but in 1978 the US Congress passed the *Energy Tax Act*, allowing tax incentives for gasoline blends with at least 10% ethanol (a four cents per gallon tax break). The *Energy Security Act* reinforced this trend and set the stage for the development of the American fuel ethanol industry, which was centered in the US *Corn Belt*[13].

Some developed countries that cannot be competitive producing ethanol from agricultural products (e.g. beat, sugarcane, corn, and other seeds) without providing subsidies, are investing on innovative technologies such as the hydrolysis of lignocellulose materials. In the past, acid hydrolysis was used to produce ethanol from wood, but efforts were abandoned due to high investment requirements. Currently, various studies are being carried out on enzymatic hydrolysis processes, with encouraging results so far. This will be further discussed in this report.

It is important to point out that the energy balance within the production process has become a crucial issue for the sector. The main reason for this is that ethanol is accepted as a viable and fast-penetrating alternative for reducing Greenhouse Gas (GHG) emissions by displacing fossil fuels (gasoline and diesel oil) in the transport sector. In this respect, sugarcane has an enormous advantage over corn and other raw materials: within the industrial process for ethanol production from sugarcane, a considerable amount of bagasse is generated, providing an excellent fuel source after the juice-extraction process. The sugarcane bagasse generated during this phase is more than sufficient to provide for the mill's energy needs plus generate a surplus for export to the grid (SMA, 2004).

AIII-5.2. 3 AIII-5.2.3 Fuel ethanol in Brazil

Sugarcane is produced in more than a 100 countries around the world with an estimated global production of 1.3 billion tons per year (FAO, 2004). Brazil is the largest producer with 350 million tons harvested in the 2003/2004-crop season. Sugarcane tradition in Brazil dates from the beginning of the 17th century. Despite several attempts to promote ethanol as a fuel during the 20th Century, the sugarcane sector remained essentially devoted to the sugar production. Ethanol was a mere by-product produced from the low-cost *molasses*, a byproduct from the sugar production process. At the 1973 oil crisis, Brazil was heavily dependent on imported oil (around 80%). Consequently, high oil prices significantly

13 Corn Belt: an agricultural region of the U.S. Midwest, where corn is the principal cash crop. Located in the north central plains, it is centered in Iowa and Indiana, most parts of Illinois and extends into Minnesota, South Dakota, Nebraska, Kansas, Missouri, Indiana, Ohio, and Wisconsin. Large-scale commercial and mechanized farming prevails in this region of deep, fertile, well-drained soils and hot, humid summers.

affected country's finances and added concerns regarding secure supplies. All these factors, in conjunction with low international sugar prices and the large investment already committed in the modernization of the sugarcane sector, motivated the Brazilian Government to establish the ProAlcool. Indeed, there was a very favorable scenario for the development of the ethanol industry anchored in the sugar mill complex.

The annual ethanol production increased very rapidly from a 600,000 m^3 plateau in the early 1970s to 3.4 million m^3 in 1979, reaching 12.3 million m^3 in 1986. By mid 1980s, the scenario had changed considerably: oil prices dropped significantly, and the international sugar market was again very attractive. Under this scenario, the ProAlcool lost its momentum and between 1985 and 2000 ethanol consumption remained at around 11 million m^3 per year. During this period, the demand for anhydrous ethanol (used in the 22% ethanol-gasoline blend) increased steadily, while the consumption of anhydrous ethanol (used in *neat ethanol cars*) dropped because the aging of the existing ethanol fleet (from 5.5 million to less than 3 million vehicles). Efforts by the Brazilian Government and ethanol producers revived the ProAlcool late in the 1990s, motivated by high oil prices, and a strong devaluation of the Brazilian currency (Real), making the ethanol produced in Brazil very competitive[14] when compared to gasoline. The advent of the Brazilian version of flexible-fuel vehicles (FFV), once again changed the scenario, bringing back the confidence of Brazilian consumers in ethanol-fueled cars. Presently, FFV's represents over 27% of new car sales (see Table 5.8.1a).

Three main reasons have combined to bring competitiveness back to the ProAlcool:

- Technological innovations, which led to rapid reduction costs while increasing productivity;
- Escalation of oil prices in the international market. Currently, it is estimated that ethanol can compete with gasoline, without fiscal incentives or subsidies; and
- Favorable currency exchange rate.

AIII-5.2. 4 AIII-5.2.4 Technological Development

Technological development was a high priority. The sector planning for the first phase of the ProAlcool included significant efforts to rapidly increase sugarcane and ethanol production, in order to meet production goals set by the Federal Government. At that time, very little attention was paid to efficiency and cost reduction.

During the second phase, when production was reaching a new plateau, the sector was mostly concerned with increasing efficiency, productivity, and cost reduction. During the third and fourth phases, there was significant interest on management improvement by the use of adequate tools and modern practices. All these factors allowed the industry to master the whole process.

The cost of sugarcane delivered at the mill, represents nearly two thirds of the final ethanol cost. Therefore, productivity has earned the priority on R&D programs. The focus turned to

[14] **Even in the total absence of incentives or subsidies.**

the development of new and improved varieties allowing: (1) higher yields; (2) higher sugar content; (3) greater resistance to diseases; and (4) flexibility to adapt under different production environment (e.g. soil and microclimate conditions). Improved agricultural practices (e.g. soil preparation, planting, fertilizer and herbicide application, pest control, more efficient transport system, and mechanization, especially for harvesting) undoubtedly helped reducing costs. Between 1975 and 2000, sugarcane yields improved by 33%, and sugar content increased 8.5%.

The use of biological pest control, for the *sugarcane borer* and the *froghopper*, had a significant positive impact both on lowering costs and on the environment. Recently, biotechnology has earned a special consideration; the *Sugarcane Genome Project* was successful in concluding the mapping of more than 40,000 genes, allowing the development of transgenic varieties, some of which are already being tested[15].

The two phases where the highest losses occurred (the juice extraction and the fermentation processes), went through a significant improvement procedure focusing on technology development. Mills had their capacity improved by over two folds by means of optimization of the mill design and improvement in sugarcane preparation. Extraction efficiency increased from 90% to 97.5% (best value) by implementing new imbibition systems; improving mill settings and automation. In addition, the use of improved materials, better sugarcane cleaning systems, and improved lubrication practices, reduced maintenance costs.

Fermentation efficiency increased from around 82% in 1975 to more than 91% (peaking at 93%) in the early 1990s. Fermentation period was reduced from around 16 hr to less than 9 hr (best values around 6 hr). Improvements can be credited to improved microbiology knowledge; application of the "fingerprint" technique to *yeast strain* selection process; enhancement of the monitoring and control processes; improved laboratory techniques; and training of personnel. Undoubtedly, plant automation has played an important role in the improvement of factory recovery and capacity.

The distillation process suffered very little changes; however, current efficiency approaches 99.8%. The ethanol dehydration process has been subjected to some changes with impacts on energy consumption (e.g. cyclohexane was substituted for benzene in azeotropic dehydration systems, mainly because of health concerns; and systems based on monoethilene glycol and molecular sieves are gaining acceptance in the distilleries due to their lower steam consumption, in spite of their higher investments costs).

The combination of all the above discussed factors has brought down ethanol costs to about US$ 0.18/liter.

15 Thus far, there are no commercial transgenic sugarcane crops in Brazil.

AIII-5.2. 5 AIII-5.2.5 Fuel ethanol use

Initially, the large-scale use of ethanol fuel was attempted by blending ethanol with gasoline. Due to blend stability problems, the water content was kept at a minimum and the anhydrous ethanol specification limited to 0.5% v/v. This solution had the advantage of fast penetration in the fuel pool, mainly because it required little or no modifications in existing engines. It also allowed some flexibility in adjusting the market (supply to the demand), as the percentage of ethanol in the gasoline fuel could vary within some limits. The main disadvantage of this option was that it placed a cap on the amount of gasoline that could be displaced by ethanol, since higher levels of ethanol in the blend would require extensive modifications to the existing engines (e.g. materials, air/fuel ratio, spark setting).

To increase the potential for gasoline displacement by ethanol, the Federal Government pressed domestic automakers in the late 1970s (Ford, Volkswagen, General Motors and Fiat) to develop and to offer to the market *neat ethanol* options for existing models. In 1978 Fiat produced the first commercial model running on pure ethanol; for this application, due to economic considerations, it was selected the azeotropic mixture of ethanol and water, the hydrous ethanol, which had an upper limit for water content of 4.5% v/v. The performance of the *neat ethanol engines* was very poor until 1983 when Ford started to power its models with an engine developed and adapted to ethanol fuel, taking advantage of some characteristics of ethanol compared to gasoline: higher octane level and vaporization heat, lower upper cycle temperature and higher compression ratios[16]. In addition, materials and corrosion-resistant coatings started to be used. The introduction of electronic injection systems in the early 1990s demanded improvements in fuel ethanol specifications, which were promptly met by producers[17].

The success of *neat ethanol cars* in the beginning of the ProAlcool was brought to an end in 1988 when a fuel shortage caused a loss of confidence among users. The sales of ethanol cars dropped drastically reaching near-zero levels in mid 1990s. After 2000, low ethanol prices and climbing international oil prices triggered, though timidly, a renewed public interest on this fuel. The introduction of Flexible Fuel Vehicles (FFV) in 2003 also boosted ethanol sales. Current ethanol prices offer an advantage to the consumer compared to gasoline-fuelled vehicles.

Currently only about 3 bbl/yr (billion litres) of ethanol fuel is traded, with Brazil and the USA being the main exporters, and Japan and EU the main importers. Japan is currently considering blending ethanol with gasoline with an initial potential market of 6 bbl/yr,

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16 The octane number (ON) of ethanol allowed the use of higher compression ratios in the in neat ethanol engines (around 13) when compared with the gasohol alternatives (around 10) what results in higher power, torque and thermodynamic efficiency; the higher value of the vaporization heat permitted the recovery of part of the thermal energy of the exhaust gas to evaporate the ethanol before entering the cylinders; lower upper cycle temperature resulted in lower heat losses to the engine coolant fluid.

17 The main changes in the ethanol specification were the establishment of limits for pH (6-8) and for some ions (iron, sodium, chloride and sulfate) aiming at the inhibition of corrosion and deposits.

although no final decision has been taken with regard to the level of blends. One of the main difficulties lies on reluctance of the Japanese to be overdependent on few ethanol suppliers. Thus, for ethanol to become a major international commodity there must be a significant number of suppliers to avoid supply monopolies or ensure a flexible enough market that ups-and-downs in supply do not affect the market in any serious way as is the case with oil. Brazil could rapidly increase its fuel ethanol production since many mills have some spare capacity, and there is also land available to expand the sugarcane area at reasonable costs.

AIII-5.2. 6 AIII-5.2.6 Environment and social aspects

The characteristics of ethanol as an octane booster and an oxygenated fuel contributed in a significant way to reduce tailpipe emissions of the existing fleet. There were CO reductions, and hydrocarbon emissions were less reactive and less toxic. In addition, NO_x levels were similar to those of gasoline engines. The blend of ethanol with gasoline made possible to phase out leaded gasoline in Brazil in 1992; in fact, Brazil was the first country in the world to adopt the use of 100% unleaded gasoline on a nationwide basis. The pollution of large metropolitan areas such as São Paulo, Rio de Janeiro and Belo Horizonte, was effectively reduced bringing health benefits to local populations. Today, the use of sophisticated electronic injection systems and three-way catalysts has brought emissions of gasoline engines to similar levels.

Currently, the sugarcane sector has largely controlled many of the impacts on the environment. For example, most of the industry's waste, stillage and filter cake, are recycled to the fields taking advantage of their fertilizing potential, and, simultaneously, eliminating residues. The use of pesticides and herbicides is significantly lower than what is required in other crops. Additionally, biological control is widely used to control pests. Pre-harvesting sugarcane burning is being phased out through legislative measurers, both at Federal and State levels.

From the global environment point of view, ethanol is a renewable fuel with near-zero greenhouse gas (GHG) emissions. A recent study (SMA, 2004) indicated that under the Brazilian scenario, for each unit of fossil energy used for ethanol production (farm and factory), 8.3 units of renewable energy are produced. The use of ethanol in substitution of gasoline avoids the emission of 2.6 kg of CO_2 equiv/liter of anhydrous ethanol or 1.7 kg of CO_2 equiv/liter of hydrous ethanol. This represents the abatement of 26 million tons of CO_2 equiv./yr, or around 9% of the country's emissions in 2000.

In Brazil, 5.3 million hectares (Mha) were used to produce 318 Mt of sugarcane in the 2003/2004-crop cycle. The area occupied by the sugarcane sector is smaller than areas used by other segments such as 6.5 Mha of planted forests (for several uses), 13 Mha for corn production, and 19 Mha for soybean. Sugarcane expansion caused by growing demand for ethanol has taken place in land previously occupied by pasture, coffee and cotton plantations.

The social importance of the sugarcane sector and the ethanol industry is enormous. The sector is responsible for more than a million jobs in rural areas. When compared to jobs associated to the production of vehicles and fuels, within a 15-year life cycle, an ethanol-fueled car provides 22 times more jobs than a conventional gasoline-fuelled car. Although approximately 60% of sugarcane crops belong to the mills, there are more than 60,000 independent sugarcane producers in the country.

AIII-5.2. 7 AIII-5.2.7 Final comments

The fuel ethanol program in Brazil, the largest renewable fuel program in the world, is now consolidated and self-sustained without subsidies. Ethanol is currently economically competing with gasoline in the international market. Favorable impacts of ethanol use on the environment, job creation in rural areas, and the foreign exchange savings, have guaranteed Federal Government support. Technological development made possible a significant reduction of production costs, making ethanol competitive with gasoline – a unique situation in the world. The simultaneous production of sugar and ethanol in sugarcane processing mills (for several years the ethanol share in the total sugarcane use has been around 50%) have brought a good synergism to the process resulting in a better sugar quality; optimization of energy consumption; flexibility in the production of sugar/ethanol; higher fermentation yields; and gains in net present value of the sector.

The ethanol fuel transportation, distribution, and retail sales are well established in the country. Every gas station in Brazil of which there are more than 27,000, has at least one operating ethanol pump. All gasoline sold in the country has 20% to 25% ethanol blend.

Finally, and considering the similarities of Latin American countries, the Brazilian Ethanol Program could be easily replicated in other countries in this area, and around the world. It is difficult to produce reliable projections for demand of renewable liquid fuels beyond 2012. There are many uncertainties related to crucial variables such as the ratification of the Kyoto Protocol, policies required to meet country's individual commitments with the reduction of GHG emissions, penetration of other forms of renewable energies in the market, technology development, and barriers for an international market implementation. However, current trends indicate an increasing role for fuel ethanol around the world, whose demand can surpass 60 billion litres by the end of the decade.

AIII-5. 3 Hydrolysis of Cellulose Materials and Ethanol Production

AIII-5.3.1 Introduction

Conversion of lignocellulosic materials to fermenting sugar by hydrolysis (acid and enzymatic) followed by fermentation of resulting sugars to ethanol, could be the way for obtaining alternative fuel from cellulose-containing materials.
Cellulose residues are the cheapest source of fermentable sugar. Nevertheless, the process of recovering carbohydrates from the recalcitrant cellulose-hemi cellulose-lignin and the difficulties related to the fermentation of these sugars makes the production cost of ethanol currently unfeasible.

Considering the ethanol fermentation step, the yeast Sacharomyces cerevisiae is able to ferment most six-carbon sugars but it does not ferment pentose sugars; as any hydrolysis process, the pentose fraction is currently discarded. Significant developments are being achieved with the aim of selecting genetically engineered microorganisms capable of converting pentose to ethanol. Some positive results have already been obtained at laboratory scale, although we are years away from commercial viability of any strain.

AIII-5.3.2 Hydrolysis processes: present and future

Process development for conversion of cellulose containing materials to reducing sugars and final ethanol production can be grouped into three main categories:

- Concentrated acid processes.
- Diluted acid processes.
- Enzymatic processes.

Concentrated acid processes use sulfuric acid as the pretreatment agent followed by a dilute acid hydrolysis step. The concentrated acid disrupts the hydrogen bonding between cellulose chains, converting it to a completely amorphous state. Once the cellulose has been decrystallized, it forms a homogeneous gelatin with the acid. The cellulose is extremely susceptible to hydrolysis at this point. Thus, dilution with water at modest temperatures provides complete and rapid hydrolysis to glucose, with little degradation. Two groups in the United States are currently working in this technology, Arkenol (Sacramento, CA.) and Masada Resource Group (Mission Vieja, CA.).

Yields obtained are high but the process still requires high investment cost in equipment while the recovery of sulfuric acid is high-energy intensive and there are also problems associated with equipment corrosion.

Hydrolysis reaction generates undesirable decomposition products like furans, low molecular weight organic acids, and phenol-based compounds that inhibit ethanol fermentation. The technology is under development and there are no plans for commercial facilities in a near future.

Diluted acid processes generally use 0.1% to 0.7% sulfuric acid as catalyst. Hydrolysis occurs in two stages to maximize sugar yields from the hemi-cellulose and cellulose fractions of biomass. The first stage is operated under milder conditions to hydrolyze hemi cellulose, while the second stage is optimized to hydrolyze the more resistant cellulose fraction. Steam explosion alone or with addition of sulfuric acid or sulfur dioxide are common pathways to loosen the strong lignincellulose complex, during the first step.

BCI and CASH, both based in the USA, have developed this process. BCI installed facilities to develop a process for conversion of sugarcane bagasse to ethanol. The unit will initially produce 72,000 m^3 per year of ethanol, utilizing an existing ethanol plant located in Jennings, LA. Dilute acid hydrolysis will be used to recover sugar from bagasse, using genetically engineered organisms to ferment the sugars from bagasse to ethanol.

The drawbacks of dilute acid process include acid corrosion that requires high investment in equipment, low yields and weak sugar concentration in liquor; high inhibitors content which makes fermentation very difficult, high energy demand and a large volume of final liquid wastes.

Enzymatic processes use cellulose as the catalyst for cellulase hydrolysis. Pretreatment of the biomass is required to make the cellulose more accessible to the enzymes. Many pretreatment options have been considered, including both thermal and chemical steps. The first application of cellulase enzyme for hydrolysis of wood to ethanol was a two stage process, first a saccharification step, followed by a separate ethanol fermentation (SHF). The most important process improvement made for the enzymatic hydrolysis of biomass was the introduction of simultaneous saccharification and fermentation (SSF), patented by Gulf Oil Company and the University of Arkansas. This new process scheme reduced the number of reactors involved by eliminating the separate hydrolysis reactor and, more importantly, avoiding the problem of product inhibition associated with enzymes. In the SSF process cellulase enzyme and fermenting microbes are combined. As the enzymes produce sugars, the fermentative organisms convert them to ethanol.

Petro-Canada, the second largest petroleum refining and marketing company in Canada, signed an agreement with Iogen Corporation in November of 1997 to co-fund R&D on biomass-to-ethanol technology. Petro-Canada, Iogen, and the Canadian government are funding the construction of a demonstration plant, based on Iogen's proprietary cellulase enzyme technology.

BC International (BCI) will begin operation of its plant using dilute acid hydrolysis technology. The choice of dilute acid technology is strategic, in that it allows for the eventual addition of enzyme hydrolysis when cellulase production becomes cost-effective. BCI is currently evaluating options for utilizing enzyme; and utilize cellulosic enzymes in a project partially funded by DOE that will lead to a commercial rice straw to ethanol facility in Gridley, CA. During many years the DOE has been developing and testing at pilot scale an enzymatic process using both paths, SHF and SSF.

In Sweden, a fully integrated pilot plant for ethanol production from softwood, comprising both two-stage dilute acid hydrolysis and the enzymatic process, is now being constructed in Ornskoldsvik, financed mainly by the Swedish Energy Administration.

The current high cost of cellulase enzymes is the key barrier to economical production of bioethanol from ligno-cellulose materials. The two largest global enzyme producers, Genencor International and Novozymes Biotech Incorporated, are working in the development of the cellulase enzyme complex to achieve a tenfold reduction in the cost of these enzymes. The presence of inhibitors from pre-treatment stage also makes the fermentation step very hard.

AIII-5.3.3 Hydrolysis in Brazil - state of the art

It is well known that Brazil in general, and the sugar and ethanol sector in particular, have offered exceptional opportunities for introducing commercial production of ethanol from cellulose materials, given its considerable experience in producing ethanol and bagasse utilization which offers one of the best lignocellulosic resource for hydrolysis.

Bagasse has probably the lowest cost compared to other sources, it is available at the production site, and it does not need practically any prior treatment for processing. Bagasse price is directly related to prices of primary fuels. Sugar and ethanol production generates an excess of bagasse and if required, the available quantity can be increased. Agricultural trashes are discarded today at the crop site but it could be forecasted as a novel resource for hydrolytic conversion by direct use or by substituting for bagasse as the fuel used by the sugar sector.

Many experiments related to hydrolysis of cellulose were done in Brazil during last 25 years. The pioneering work of INT (Brazilian Institute of Technology), in Lorena (São Paulo State), with dilute acid process is particularly remarkable. It was followed by the establishment of a joint venture involving COALBRA and Curvelo industries, allocating significant investments in the construction of a demonstration plant for wood hydrolysis by diluted sulfuric acid followed by ethanol fermentation, based on Russian technology. Unfortunately, efforts failed to produce any commercially viable processes.

At the present time, there is only one active group working in this area, developing the DHR process for Hydrolysis conversion of bagasse to ethanol.

This group started to work near 15 years ago headed by Dedini Industries, the larger supplier of equipment for sugar and ethanol sector, which owns the patents related to this technology. FINEP (a Brazilian Federal Research Financing Institution) sponsored this work.

The DHR process is being developed by Dedini Industrias de Base, CTC-Copersucar (Copersucar Technology Center), FAPESP (Sao Paulo State Research Foundation) and Dedini Agro Industrial, which are putting considerable effort to ensure the commercially feasibility of this technology. Although the DHR is being developed for bagasse, other cellulosic-containing materials could be employed. This diluted acid conversion process uses sulfuric acid as the catalyst, and no pretreatment for raw material is required.

DHR differs from the technologies being studied abroad because it is based on the Organosolv process, characterized by the use of a mixture of ethanol and water as solvent capable to dissolve lignin efficiently, exposing cellulose to a more efficient acid attack. The bagasse is fed to the hydrolysis reactor through a conical screw (very similar to systems used for feeding fibrous materials in pulping processes) capable of raising steam pressure of the reaction mixture to 26 to 29 bars.

The water-solvent solution is heated up to reaction temperature (180 - 200ºC) and introduced into the reactor together with the sulfuric acid catalyst in the proportion of 0.1- 0.25%. The mixture of the bagasse with the acid and the hot solution remains into the reactor sufficient time to provide lignin dissolution and hydrolysis of hemi cellulose and cellulose. Residence time is short enough to limit the degradation of sugars, mainly glucose, to a value economically acceptable. The reaction mixture leaving the reactor is rapidly cooled against fresh hydro-solvent solution entering the system, preventing degradation reactions to occur. The reaction mixture is then fed to a distillation column in which the solvent is recovered at the top. The lignin precipitates when the solvent is removed during distillation. The liquor containing the sugars and suspended lignin is recovered at the bottom of the column.

After a primary treatment, the hydrolytic liquor is ready for ethanol fermentation. The fermentation step is also done in a unique condition, as the liquor is blended with sugar cane must in order to control the inhibition of undesirable hydrolysis by-products.

The expectations of this process are high as it has been tested for several years at bench scale, and yields are near 59% reducing sugar conversion. Blends containing up to 35% of hydrolysis liquor (80 kg/m^3 reducing sugars) and standard must (molasses and syrup from sugar cane), were successfully fermented to ethanol (8.5 ºGL) with 89% yield.

A preliminary calculation of investment and production cost, based on bench scale data shows that the process is promising. DHR is being tested at pilot demonstration scale (50 ton/day of bagasse[18]) with the aim of optimizing the process, obtain a reliable mass and energy balance, solvent losses and design data for scaling-up the process. If the break-even point of 100 liter of ethanol per ton of bagasse is attained, a commercial unit (60 m^3/day of ethanol) will be built. Ethanol production cost will gradually diminish by optimization of hexoses yield and energy consumption.
Long-term development benchmark will be pentose fermentation to ethanol (expand).

AIII-5. 4 Ethanol from Cassava and other Biomass Sources

AIII-5.4.1 Introduction

Cassava, Manihot esculenta, is a tuberous edible plant of the spurge family (Euphorbiaceae), also called manioc or yucca. It is a perennial bush plant native of South America, especially Brazil. Cassava's roots are used for wide variety of products e.g. flour, breads, alcoholic beverage, etc. The most important part of the plant is located in its roots, which are rich in starch[19].

Cassava is a very important staple food in many developing countries, where it is the basic source of nutrients for 500 to 700 million people within the tropics, particularly for the poor. It is widely cultivated in several countries (e.g. Indonesia, Malaysia, the Philippines, Thailand, Nigeria and other parts of Africa), assuming great social importance. Brazil is the second largest cassava producer in the world, after Nigeria, with a total production of 22.3 million tons of roots in 2002 (Nigeria with 30 million tons). According to the Brazilian Institute of Statistics and Geography (IBGE), the area cultivated with cassava in Brazil was 1.6 million hectares in 1996.

Cassava easily adapts to a wide range of climates. It is capable to withstand droughts, heavy rains, and is often the sole source of food for the poor. As with sorghum, numerous studies have been carried out to test its feasibility as ethanol feedstock. For example, in Brazil in the

18 Bagasse implies 50% moisture content, as it comes out from the juice extraction process.
19 Starch $(C_6H_{10}O_5)_n$ is a polysaccharide.

late 1970s there was a large cassava-based ethanol program of about 0.5 Ml. However, cassava failed for a combination of reasons:
High costs (i.e. cassava roots have to be to first hydrolyzed to fermentable sugars);
Lack of experience with commercial plantations;
Competition with sugarcane.

More recently, countries like China, Thailand, and Philippines, have shown interest in obtaining ethanol from cassava. South Africa has also considerable potential but there is no experience or any major plan. Thailand in particular plans to produce ethanol primarily from cassava and sugarcane molasses. One reason is that Thailand produces large surpluses (e.g. total production in 2002 was about 18-20 million ton/yr, of which 14 million ton/yr were exported compared with a domestic consumption 2 million ton) which are finding increasing difficulties to find markets; and the same applies to molasses of which there are about 1 million ton/yr of surpluses. To the best of our knowledge there are not any other countries planning to use cassava as ethanol feedstock in any significant scale.

AIII-5.4.2 Productivity of cassava

The average productivity of the cassava in 2001 was of 13.7 ton/ha ("*in natura*"). The productivity of the total aerial part is similar to the one of the roots. Nevertheless, the percentage of used parts depends on the development of the plant and from the quality being required. The usable percentage of the plant could reach up to 80% in cultures with less than 12 months of age.

Cassava is a crop with considerable potential for increasing productivity e.g. it mostly grown in small plots using traditional methods, with little or not modern inputs. Its morphological characteristics allow to take advantage of long periods of abundant rains and thus to withstand long droughts. In favorable conditions of climate and soil, productivity may reach up to 71.4 ton/ha of "*in natura*", corresponding to 25 ton/ha.yr of dry matter (SILVA, et al., 2002).

By-products and residues from the extraction of starch for added value products can be used to generate energy, supporting what is a popular knowledge: "cassava has a high-attached value".

AIII-5.4.3 Energy use of Cassava

Cassava's main energy application is in the production of ethanol. However, due to the difficulty involved within the preliminary stages (after the conversion of the starch into sugar the process is similar to that that uses the sugarcane), costs associated to the industrialization of the cassava do not allow the expansion of this energy alternative. Countless experimental facilities were shut down or converted to sugarcane power plants. Table 5.4.3 compares productivity of sugarcane and cassava.

Table 5.4.3 Ethanol potential from Sugarcane and. Cassava

BIOMASS	PRODUCTIVITY (ton/ha)	YIELD (liter/ton)	YIELD (liter/ha)
Sugarcane	80	80	6,400
Cassava	14*	180	2,520

* in natura

Source: EMBRAPA, 2003

Residues from the ethanol production from starch also have an energy application. It can reach a productivity of 12 ton/ha.yr, with a heating value arriving at 15.76 MJ/kg. There little experience with large-scale commercial plantations of cassava, except in some industrial countries.

Producing ethanol in large scale from cassava may be the best option for countries with large-scale production and historical experience with this crop e.g. in Brazil with a highly competitive sugarcane industry, cassava may not be the alternative to produce ethanol despite the role it plays in the country. However, ethanol from cassava may be the most feasible alternative for regions with unfavorable weather or deprived soils, where the cassava can offer better yields.

AIII-5.4.4 Feasibility of ethanol production from other biomass sources

The following is a brief description of some of the additional raw materials that can be used in the production of ethanol.

AIII-5.4.4.1 Sweet Sorghum (poaceae)

- Sweet Sorghum offers good possibilities, primarily as an intermediary crop with sugarcane, particularly in China, and Southern Africa. Its advantages include: short growing cycle (4 months), resistance to droughts and lower water requirements; propagation (e.g. 4.5 kg/ha compared to 4500-6000 kg/ha of sugar cuttings), potential high productivity (e.g. 7,000 to 8,000 l/ha of ethanol has been reported); etc. There are a few problems, including:
- difficulties with transport (high biomass mass);
- fermentation problems;
- rapid decaying;
- small-scale farming e.g. although 90% of area is in developing countries, over 60% of total production takes place in industrial countries; it is produced by many low income farmers mostly for food;
- lack of experience with large-scale industrial applications; commercial plantations are mostly in the industrial countries that are unlikely to use it for ethanol production in any meaningful way due to, generally, unfavorable climatic conditions and high costs.

There have been many attempts to use sweet sorghum as ethanol feedstock, particularly in China, USA, EU, etc. In Brazil various experiments were carried out during the early stages of ProAlcool but were abandoned because the difficulties of supplementing sweet sorghum with sugarcane e.g. rapid decaying, short season which did not coincided with cane;

attitudes of sugarcane growers e.g. lack of experience with sweet sorghum, higher costs, problems with crystallizing sugar, etc.

Sorghum is native of central-eastern Africa and belongs to the botanical family of Graminaceae, genus *Sorghum* species *bicolor* (L,) [Moench]. Although its tropical origin it is well adapted to other climates. Sweet *Sorghum*, particularly, can be used for production of ethanol and its derivatives from the fermentation of sugars present in the stem juices and grains. Sweet sorghum may also supply by-products from bagasse, the remaining part of the stems after juice extraction, such as pyrolytic oils, quality fuels, pellets of carbon, synthesis gas, and lignocellulosic materials. An interesting energetic application may be electricity generation through combustion of total biomass. Sweet *Sorghum* has been investigated as a source of sugar in Italy in the past and more recently has been considered, at European level, as a crop for biomass for energy and pulp for paper production. As far as fiber concerned it has been shown that *Sorghum* produces a good quality fiber in the stalks but a low yield of biomass. Recently in Europe renewed interest in this crop has resulted from the availability of hybrids 'grain *Sorghum* x broomcorn', that provide a greater yield, resulting from the high heterosys provided by this cross. Sweet sorghum has been investigated in Europe as possible source of ethanol, but few takes is as a serious source of ethanol.

According to field experiments carried out allowed to find out that within the Mediterranean countries (Italy, France, Spain, Portugal and Greece), biomass yield of sweet and fiber *Sorghum* could be generally higher than 20 t/ha, with maximum yields around 40 t/ha in South Italy and Greece (FAIR, 2004). The biomass yield of the varieties generally increased with increasing length of the growing season: the highest yields were obtained with the latest genotypes. The different duration of the growing season determined a different thermal units requirements among the studied varieties; the thermal units ranged between 1200 and 1700 degree days which indicates the possibility to define in Europe, the genotype available for each area according to the thermal regime: the early varieties more suitable for the northern areas (France, South Germany), and the late varieties, which can be used under high temperature conditions, could be grown in all Mediterranean countries.

AIII-5.4.4.2 Corn (zea mays)

Maize is a major world crop, particularly in the USA where it is the main source of ethanol, sweeteners, and multitude of other products. In other countries e.g. China and South Africa maize could play a significant supplementary role in the future as feedstock for ethanol, but it is unlikely it will be in large scale due to high costs, lower productivity, high demand for other products such as sweeteners, etc. This could change significantly if ethanol can economically be obtained also from corn stover. By-products play a key role in the economics of ethanol from maize.

The productivity of corn varies considerably depending on the specie, soil fertility, and crop management, but generally ranges from 2.5 to 7.5 ton/ha. However, with the improvement of production technologies, it may be possible to reach higher productivities. Brazil's corn crop has a low average productivity of 2.6 ton/ha and is considered very low when compared to US with of 6.5 to 7.5 ton/ha. Additionally, the US is the world largest producer of corn-derived ethanol, with an annual production in 2003 of 10.6 million m^3.

AIII-5.4.4.3 Babassu palm (orbignya species)

Babassu grows wild in tropical Northeastern Brazil. The kernels of its hard shelled nuts are the source of oil, with similar properties and uses to coconut oil. The babassu nut is one of the most promising alternative energy sources. It is estimated that there about 15 Mha in Brazil where babassu plants grow extensively.

Babassu's productivity varies from 2 ton/ha to 15.6 ton/ha of babassu coconut/ha.yr possessing a 70% starch stock in the plant's body. Babassu coconut can reach productivity of 1.6 m^3/ha of ethanol.

AIII-5.4.4.4 Switchgrass (pennisetum purpureum schum – elephant grass variety)

Miscanthus, reed canary grass and switchgrass are the three herbaceous perennial grasses currently being evaluated as potential energy sources in various countries.

The potential of switchgrass (Panicum virgatum L.), a C4 grass, as an energy source, has been extensively researched in the USA, where it is very well adapted to most Northern America conditions and thus quite suitable for cofiring. This grass can be directly burned or mixed with other fuel sources such as coal, wood, etc. Switchgrass grows in a thick cover and can reach about 2.5 meters high, and it is an excellent energy source, and also provides a good cover for wildlife and prevents soil erosion. Switchgrass is a long-lived perennial plant that can also produce high yields on marginal soil with a low establishment cost. It is cold tolerant, and requires low inputs and is adaptable to a wide geographical area. For these reasons it has also attracted considerable attention in the UK and in the EU in general. However, much still needs to be learned at a practical site-specific level to be able to consider this grass as a serious contender for energy.

The switchgrass is a high-productivity gramineous (12 to 20 tons/ha.yr of dry matter). Comparatively, eucalyptus crops allow between 20 and 30 tons/ha.yr of dry matter. Its energy use in the form of charcoal allows an average 25 to 30 MJ/kg (dry basis), similar to eucalyptus charcoal. This is still in an experimental stage (IPT, 2003).

AIII-5. 5 Biodiesel

AIII-5.5.1 Introduction

Biodiesel (Free Fatty Acid Methyl Ester) is a fuel made from organic oils. It is made through transesterification whereby the glycerin is separated from the fat or vegetable oil. The process generates two products: methyl esters (Biodiesel) and glycerin (a valuable byproduct usually used in soaps and other products). Biodiesel can be burned in standard diesel engines. It is also possible to make biodiesel from waste cooking vegetable oil. The transesterification procedure requires methanol (CH_3OH) (or Ethanol) and sodium hydroxide (NaOH), commonly known as lye or caustic soda, combined to form a mixture known as sodium methoxide (Na^+ CH_3O^-). The sodium methoxide, when mixed with the vegetable oil causes it to breaks into glycerin and esters or biodiesel.

Biodiesel can be blended at any proportion with petroleum diesel to create a biodiesel blend. It can be used in compression-ignition (diesel) engines with little or no modifications. Biodiesel is simple to use, biodegradable, nontoxic, and essentially free of sulfur and aromatics.

Independently of its origin (the raw material it derives from) the transesterification agent (ethanol or methanol) used, the end-product is completely mixable with petroleum diesel. Mixtures can be used in any proportions. Biodiesel blends are denoted as "BXX" with "XX" representing the percentage of biodiesel contained in the blend.

The main advantages of the biodiesel fuel include:

Reduction of levels of local emissions of sulfur and particulates: biodiesel is non toxic and biodegradable;

Biodiesel can be made from several renewable resources such as African palm, castor bean, soybean, etc. Consequently, its use reduces dependence on foreign oil.

AIII-5.5.2 Biodiesel in the world

Common sources of vegetable oil include: (1) Oilseeds: flax seed, hemp (cannabis), linseed, rapeseed, canola (a special variety of rapeseed, bred to minimize toxin content), safflower, sesame, sunflower, grape seed; and (2) other common vegetable oils: almond, avocado, castor bean, corn (maize), cotton seed, coconut, hazelnut, olive, palm (from the fruit of the African palm tree), palm kernel oil (from the seed of the African palm tree), peanut, pumpkin seed, rice bran, soybean, walnut. Table 5.5.2 indicates the most used vegetable oils in the world.

Table 5.7.2. Total World Consumption of major vegetable oils (2002)

Oil Type	**Consumption (million tons)**
Soybean	26.0
Palm	23.3
Rapeseed	13.1
Sunflower seed	8.6
Peanut	4.2
Cotton seed	3.6
Palm Kernel	2.7
Olive	2.5

Note: these figures include industrial and animal feed use. The vegetable oil most widely used in human nutrition is sunflower seed oil. Palm oil, which is solid at room temperature, is used mainly to produce soaps and cosmetics. The majority of European rapeseed oil production is used to produce biodiesel.

Currently, several countries produce biodiesel commercially or stimulate the development of biodiesel in industrial scale, including Argentina, the United States, Malaysia, and the European Union.

In 2001, the world production of vegetable oils was approximately 90 million tons (FERRES, 2002), providing a sustainable base for biodiesel production. Since 1990, biodiesel from colza and sunflower were commercialized several nations within the European Community. European automakers have accepted, without any restrictions, the use of blends containing up to 5% of biodiesel for conventional engines; in several cases, automakers approved the use of blends containing up to 30% of biodiesel. Annual biodiesel consumption in Europe reached 427,000 ton in 2000. In Germany, 315,000 tons were used in order to supply an existing fleet of light, heavy, and public transportation vehicles running with 100% biodiesel (ROSE, 2002).

In the United States, since March 2002, diesel fuels sold in the state of Minnesota had to be, when available, by force of law, blended with 2% of biodiesel. In Malaysia, a biodiesel program is currently under implementation. The first domestic biodiesel production facility becomes operational in 2004, with a production capacity of 500,000 tons per year. Argentina has recently implemented a fiscal incentive program in order to allow biodiesel to compete with its petroleum equivalent. This incentive program will be in force during the next ten years, when biodiesel is expected to be competitive.

AIII-5.5.3 Biodiesel in Brazil

The biodiesel experience in Brazil started in the 1970s mainly based on soybean oil, including tests in urban buses.

Since 1991, sectors of the Federal government have been motivating the development of renewable fuels with the support of the *Global Environmental Facility* and the European Community.

In 2000, a private company called ECOMAT located in the state of Mato Grosso, installed a industrial facility for the production of a stabilizing additive used in ethanol-diesel blends. This facility is capable of producing soybean diesel using either ethyl or methyl esters.

In 2003, the immediate Brazilian readiness for the production of biodiesel from soybean concentrates on the perspective of its nominal production capacity (in the order of 51 million tons), its processing capacity (in the order of 36 million tons), its corresponding soybean oil production capacity (in the order of 5 million m^3), and its biodiesel production capacity (in the order of 1.5 million m^3), being 47% in the central region and 40% in the Southern region.

The oil of the African palm (*Elaeis guineensis*) has been increasing its participation in the international vegetable oil market. This palm oil should surpass soybean by 2010 (31 million ton/yr). Brazil is the nation with the greatest potential for expanding the agricultural production of the African palm, mainly because of the availability of productive land. Consequently, a Federal program named *PROBIOAMAZON* was established and presently generates incentives to allow an annual production of 500,000 tons of palm oil in the Northern region.

Concomitantly, the Brazilian government works on the expansion of agricultural frontiers for soybean and on the development of technologies for the processing of the palm oil based on the following considerations:
Palm oil prices are being reduced at a rate of 3% per year (average of the past 20 years) and;
Petroleum diesel prices are increasing, and the trend is expected to continue for the foreseeable future.

The annual consumption of petroleum diesel in Brazil is approximately 36 million m^3, and 20% of this fuel comes from imports. In Brazil, diesel is preferentially used for public cargo and transportation (80%); 20% is used for electric generation in isolated areas, agricultural industry, and for emergency backup systems (thermoelectric power units - 1,000 MW).

AIII-5.5.4 Economic implication

Efforts are under way in several nations in order to bring biodiesel production costs to competitive levels with petroleum diesel. In Brazil, viability of biodiesel fuels still depends on the identification of a suitable substrate that could be feasible for large-scale production, and could be introduced in the complex Brazilian market.

The history of the Brazilian sugarcane ethanol industry, which was in a similar situation around 1975, struggling to compete with gasoline, suggests that biodiesel can become viable soon. Existing cost data shows considerable cost variations, mainly as a consequence of the raw material used to extract the oil.

A recent study undertaken by ABIOVE (FERRES, 2002) indicates that production costs for the specific case of soybean diesel (within Sao Paulo and Paraná States) is between US$ 300 and US$ 380 per m^3. Within the Brazilian central region, costs range between US$ 770 and US$ 830 per m^3.

An analysis made by IVIMG - COPPE (ROSA, 2002), considered several sources of vegetable oil. Results indicate costs of US$ 470 per m^3 for soybean oil, US$ 800 per m^3 for castor bean oil, and US$ 720 per m^3 for babassu palm oil.

A study prepared by the Brazilian Petroleum Agency (ANP), simulated a scenario where 100% of the diesel fuel in Brazil would be replaced by a blend composed of 5% of biodiesel and 95% of petroleum diesel. Under this hypothetical scenario, diesel imports would be reduced leading to annual savings in the order of US$ 350 million. However, in order to make biodiesel competitive with petroleum diesel, annual tax incentives in the order of U$ 323 million would have to be granted. Subsidies currently being provided to petroleum diesel fuel, however are not being internalized in these studies.

Electricity generation could be added to the demand of the transportation sector, turning a national program feasible by providing financial attractiveness at national level, including significant savings to isolated communities.

AIII-5. 6 Bio-oil by slow and fast pyrolysis of biomass

AIII-5.6.1 Introduction

The main advantage that pyrolysis offers over gasification is a wide range of products that can potentially be obtained, ranging from transportation fuel to chemical feedstock. Considerable amount of research has gone into pyrolysis in the past decade in many countries. After many ups-and-downs, the first commercial plants are coming into operation. Any form of biomass can be used (over 100 different biomass types have been tested in labs around the world), but cellulose gives the highest yields at around 85-90% wt on dry feed. Liquid oils obtained from pyrolysis have been tested for short periods on gas turbines and engines with some initial success, but long-term data is still lacking.

Pyrolysis of biomass generates three main different energy products in different quantities: charcoal, oils, and gases. Fast pyrolysis[20] gives high oil yields, but still needs to overcome some technical problems needed to obtain pyrolytic oils. However, fast pyrolysis is one of the most recently emerging biomass technologies used to convert biomass feedstock into higher value products.

The surge of interest for pyrolysis stems from the number of multi-products than can potentially be obtained from this technology e.g. liquid fuels that can easily be stored and transported, and the large number of chemicals (e.g. adhesives, organic chemicals, and flavoring) that offer a good possibilities for increasing revenues.
Low gravimetric and energetic efficiencies are observed in today's operating carbonization processes. Recovery of liquid by-products associated to the production of charcoal is not significant. The recovery efficiency for tar[21] varies from 8% to 15% (based on charcoal produced), which is obtained in rectangular ovens. These figures represent about 2 to 4 tons produced in each carbonization cycle involving 60 to 70 wood tons (db).

Currently, charcoal production technologies based on pressurized systems and bio-oil by fast pyrolysis is not commercially available. The main projects, operational or under development, involve capacities between 20 kg/h and 4 ton/h. The main feedstock sources, depending of available technology, are agricultural, forest, and other industrial residues.

In Brazil, fast pyrolysis is a novel technology in terms of implementation. Currently, there is only one operational pilot plant for research and demonstration (R&D) purposes. This plant has a processing capacity of 100 kg/hr (dry basis) and it uses a bubbling fluidized bed reactor. This plant belongs to the Biofuel Research Group at the State University of Campinas (UNICAMP), and operates at the CTC facilities. The main issues involving fast pyrolysis currently being discussed include scaling-up, technologies, reduction costs, information dissemination on bio-oil, market development and challenges.

AIII- 5.6.2 Slow and fast pyrolysis technologies

Pyrolysis is a process that generally occurs under temperatures that vary from 400°C up to 650ºC in total or partial absence of oxygen. Gases, liquids and solids are generated in proportions that depend on the parameters considered, that is, the temperature and pressure of the reactor, the residence time of the solid, liquids and gaseous phases inside the reactor, the time and the rate of heating of the biomass particles, the reactor's internal environment, and initial conditions of the biomass.

The pyrolysis process most commonly utilized for charcoal production is carbonization. Among the main types of ovens commercialized in Brazil, rectangular ovens allow the higher efficiencies. They have high capacity for recovering tar (bio-oil from slow pyrolysis). Tar is recovered and stored for subsequent energy production. Tar can also be used in the

20 Fast pyrolysis is a moderate temperature process (450 and 600°C) in which biomass is rapidly heated in the absence of oxygen.
21 Tar: term used for designating of bio-oils of slow pyrolysis.

production of high added value products, mostly by means of distillation. A simplified global thermodynamic evaluation of the carbonization process is shown in Table 5.6.2a.

Table 5.6.2.a Global thermodynamic parameters from the V&MT carbonization process[1]

Parameters	Oven [1]			
	Charcoal production		Bio-oil production	
	Firewood	Charcoal	1st system	2nd system
Quantity, ton [3]	75	25	2 4	4
Mass efficiency of the process, %	33		8[4]	15 [4]
Chemical properties of charcoal	Moisture content = 4.5 [5] Fixed Carbon = 74 [3]			
Total Bio-Oil produced (ton / month)			350	

[1] Rectangular metallic oven with independent system of recovery of the volatile compounds and 14 days cycle of carbonization.
[2] Average values.
[3] Dry basis.
[4] Charcoal produced basis.
[5] Wet basis.
Source: V&MT, 2004

High-Yield (HY) charcoal, with 38% to 48% of gravimetric efficiency, was obtained in the Hawaiian National Energy Institute-HNEI, at the University of Hawaii. The process is based on high-pressure pyrolysis, with heating rates and controlled final temperature. The HHV (High Heating Value), fixed carbon content and volatiles content values in the charcoal were similar to the traditional firewood charcoal. The following experimental conditions of the process were optimized: pressure = 1 MPa, temperature = 450°C, and total time = 2 hours. Results obtained from different types of biomass are indicated in the Table 5.8.2b.

Table 5.6.2b. Results of the high-pressure pyrolysis of biomass

Biomass	Mass efficiency (%)*	Fixed carbon content (%)*	Volatile content, (%)*	Ash content, (%)*	HHV (MJ/kg)*
Macadamia shell	48		25.6		
Macadamia wood	43		25.4		
Eucalyptus wood	46		20.2		
Sugarcane bagasse	44		32.6		

Dry Basis
Source: ROSILLO-CALLE et al. 2000

Because of environmental and efficiency issues which need to be improved, the technology available to make bio-oil recovery systems economically feasible may not be available before 2015.

The use of biomass as liquid fuels has attracted significant interest on pyrolysis during the past two decades. he fast pyrolysis concept for organic compounds has attracted most of the attention. Some industrial sectors, chiefly concentrated in Europe and North America, are putting considerable efforts to find commercial applications for products obtained from bio-oil.

The main characteristics of the fast pyrolysis process are: short heating time for carbonaceous particles and for vapors formed within the reactor; high heating rates and mass-transfer coefficients; and moderate temperature from the heating source. In general, the residence time for vapors should be lower then 1 minute.

All fast pyrolysis technologies apply these basics principles aiming at maximizing bio-oil yield. The bio-oil formed from the fast pyrolysis of biomass is primarily tar. This product is formed from successive decomposition reactions, isomerization, cracking (split), recombination by condensation, polymerization, depolymerization and fragmentation, and has high water content in its composition. Table 5.6.2c shows the main physical and chemical properties of a typical fast pyrolysis process for the extraction of bio-oil from wood.

Table 5.6.2c Chemical and physical properties of a typical bio-oil from fast pyrolysis of wood

Physical property	Typical value	Characteristics
		Liquid fuel
Moisture content	15-30%	
PH	2.5	Ready substitution for conventional fuels
Specific gravity	1.20	in many stationary applications such as
Elemental analysis:		boilers, engines, turbines
C	54-58%	
H	5.5-7.0%	Heating value of 17 MJ/kg at 25% wt.
O	35-40%	water, is about 40% that of fuel oil / diesel
N	0-0.2%	
Ash	0-0.2%	Does not mix with hydrocarbon fuels
HHV as produced	16-19 MJ/kg	
Viscosity (50^{o}C and 25% water)	40-100 cP	Not as stable as fossil fuels
Solids (char)	0.2 – 1.0%wt	
Vacuum distillation residue	up to 50% wt	Quality needs definition for each application

Source: Czernik and Bridgwater, 2004

Over the past 20 years, many studies have been carried out on fast pyrolysis concepts and technologies. The ultimate goal is producing commercially viable large-scale bio-oil facilities for the production of heat, electric energy and chemicals.

AIII-5.8.1 AIII-5.6.3 Reactor's configurations for biomass fast pyrolysis

Some reactor configurations have been proposed for fast biomass pyrolysis. Table 5.6.3 shows a list of the main configurations and their characteristics. The actual technology and market status of biomass fast pyrolysis is summarized in Table 5.6.3

Table 5.6.3. Main Fast Pyrolysis Projects in the World

Plants (and companies)	Characteristics
Union Fenosa Company, Spain	Bubbling fluidized bed reactor, 200 kg/h capacity (deactivated)
Dynamotive Energy Systems Corporation (BioTherm™)	Bubbling fluidized bed reactor, capacity ranging from 80 to 625 kg/h: 1 plant in Canada based on Resource Transforms International-RTI, and 2 plants at demonstration scale, 1 to 400 kg/h and presently scaling up the plant to 4 ton/h
Wellman Group Companies	Bubbling fluidized bed reactor: 280 kg/h unity in UK
Ensyn Group Inc. (RTP–Rapid Thermal Processing Technology)	Circulating fluidized bed reactor: 6 plants with the largest nominal capacity of 50 ton/day operated by Red Arrow Products Company. 18 millions liters/yr of bio-oil.
National Renewable Energy Laboratory-NREL. More recently at Aston University-England	Ablative pyrolysis reactor (vortex reactor): new technologic concept. 1 second generation reactor at Aston University, UK
Georgia Tech Research Institute-GTRI	Entrained flow reactor
BTG-Biomass Technology Group and Twente University-Netherlands	Rotating cone reactor: operates a system at 5 ton/day and presently proposing scaling up to 50 ton/day
Pyrovac Group and University of Laval-Canada	Vacuum pyrolysis reactor: operates with moderated rates of heating and reduced pressures. Building a 3,5 ton/h plant

Source: Compilation of several sources cited in this section

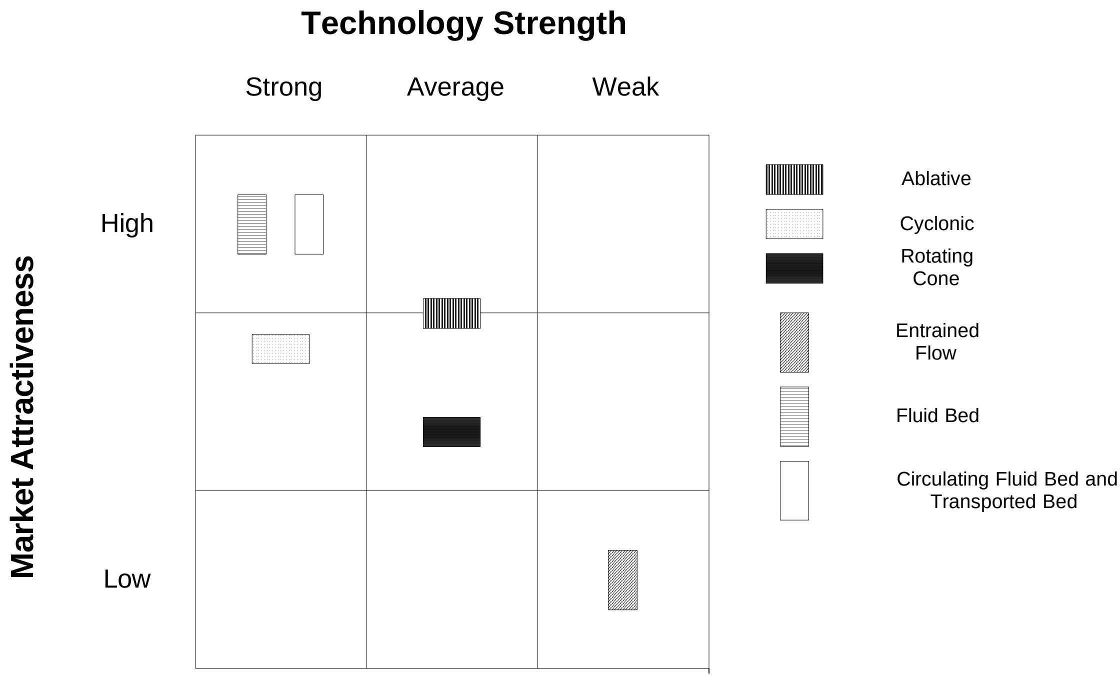

Figure 5.6.3.1. Status of Fast Pyrolysis Systems (PYNE, 2004)

AIII-5.8.2 AIII-5.6.4 Bio-oil costs and market

The potential applications of bio-oil are many and diverse, ranging from transport, stationary, gas turbines to Sterling engines. However, it is necessary to solve problems such as high viscosity, coking, corrosion, poor volatility, small heating value, and aging (polymerization reactions during storage). Orenda Aerospace Corporation, in Canada, has been developing the use of bio-oil in a 2.5 MWe class GT2500 gas turbine. Bio-oil is also a good source of specialty chemical products with very high market price. The use of fractionating techniques made possible to obtain products for the food flavoring sector. Several compositions have been patented and commercialized.

Electricity production based on bio-oil from fast pyrolysis is another alternative being presently considered in R&D projects. The main potential advantages of this application are that electricity production could be by-coupled, i.e., bio-oil produced would be transported to the energy production facility. Additional tests are required before scale-up.

The National Renewable Energy Laboratory (NREL) in Golden, Colorado, USA, did a feasibility analysis for two plants: (1) 38 ton/h (dry basis), and (2) 9 ton/h (dry basis) capacity. The study was based on a feedstock price of US$ 44/ton and an annual interest rate of 20%. Estimated bio-oil costs were in US$ 100/ton and US$ 158/ton, respectively. The results indicate the importance of scale (GREGOIRE, 1992).

A technical economic feasibility study estimates that 500 kg/hr is the lower limit for the economic viability of a fast pyrolysis plant (PAGLIAREDI et. at., 2004). The study was based on a feedstock price of US$ 10.00/ton, an annual attractiveness rate of 10%, annual interest rate of 40% and an annual operating time of 3456 hours at 12 hours/day. From this information, the estimated payback period and investment return were 3 years and 29%, respectively.

The economic feasibility of bio-oil production is very dependent on the following factors:
- market and feedstock price;
- economy of scale;
- bio-oil recovery efficiency
- financial parameters: financial settings, interest rates, taxes, etc.

AIII-5. 7 Methanol by biomass gasification

AIII-5.7.1 Introduction

Methanol is a chemical compound belonging to the family of the alcohols. Its main technical characteristic is a high degree of versatility, as it can be utilized as straight fuel or in mixtures with others fuels (ethanol, fuels derived from petroleum and bio-fuel, etc.), or even as raw material in the production of other fuels and chemical products. Under the thermodynamic viewpoint, its utilization in internal combustion engines brings some advantages as an increase in power (due to the increase of the engine's compression rate) and in energy efficiency, besides reducing the emission of pollutants. The main restraint to the use of methanol in large scale is its high toxicity when ingested. In addition, when burning, it emits a flame invisible to the human eyes. Other negative characteristics are their incompatibility with others materials when in contact with them. Although there are important environmental restraints to the use of the methanol, a considerable number of preliminary techno-economic evaluations, based in its production by unconventional and still not commercial technologies, have been done. The results show that the cost of the methanol produced from the gasification of biomass, today's most promising and researched technology (as far as renewable raw materials are concerned), varies, on average, between US$ 51 and US$ 124 per bOE of methanol (1998), which is significantly higher than the cost of methanol produced from natural gas by means of conventional technologies (US$ 32/bOE for a plant of 320 bOE/h). This analysis also suggests that the production of methanol from indirect heating gasifiers presents lower production costs than the systems based on direct heating gasifiers, and that the production costs of methanol from biomass can compete with the costs of the systems based in mineral coal, which are approximately US$ 104/bOE of methanol (for a plant of 640 bOE/h)

Methanol (CH_3OH) is currently produced mostly from natural gas and also from coal, but can also be produced from biomass and this has resulted in considerable interest lately. Methanol is a common industrial chemical that has been commercialized for over 350 years and is widely used, primarily as a building block for thousand of products ranging from plastics to construction materials (for further information: www.methanol.org).

Methanol has also been used as an alternative transport fuel blended in various proportions and is currently under consideration for wider use. Its main appeal is as a potential clean-burning fuel suitable for gas turbines, IC engines, but particularly for new fuel cell technologies. Due to the liquid properties of methanol at room temperature, ambient pressure, the high hydrogen to carbon ration, and the relatively low combustion temperature, methanol is considered as an ideal hydrogen carrier for fuel cell vehicles. This is, perhaps, the greater potential for future methanol fuel in transportation.

Methanol is a leading candidate to provide the hydrocarbon necessary to power fuel cells (FCVs). Some estimates suggest that within two decades, between 7 and 20% of new car sold could be powered by fuel cells, or about 40 million FCVs by 2020 many of which could be using methanol (for further information: www.methanol.org).

In 2000, world production capacity of methanol was approx. 12.5 b/gal (47.3 b/l/). The world methanol industry generates over $12 billion/yr and employs, directly and indirectly, over 100,000 people. Methanol was used as a transport fuel in many countries. For example, in the USA methanol has been used as a fuel in certain vehicles (e.g. race cars) either neat (100%) or blended since the 1970s, and in 1993, about 12 million gallons (45.5 million liters), and a further 212 million gallons (802 million liters) were used in California as fuel additives. The American Methanol Institute (AMI) estimates that methanol demand for fuel could reach over 880 million gallons (3.3+ billion/liters) by 2010 (PIRNIE, 1999) (for further information: www.methanol.org).

In the late 1970s, the California Energy Commission (CEC) supported various experiments with methanol fuels which continued to the mid 1980s. More than 15,000 methanol FFVs were sold, but currently only 38 retail service stations continue to sell methanol fuel. In addition to technical difficulties, price is also a major constraint, sold between $0.88 to $1.10 per gallon, which taking into account that methanol contains about 50% the energy of gasoline, takes the real price close to $1.50 per gallon. FFVs for methanol are no longer being produced.

In the early 1980s, Brazil was also considering to implement a large methanol program (45 M tons), by pyrolysis of wood from fast-growing eucalyptus. However, technical and economic considerations, together with competition and pressure from the sugarcane industry, which could produce ethanol much cheaper, prevented the program to take off.

AIII-5.7.2 Production and costs of methanol from biomass gasification

The thermo-chemical production of methanol from biomass involves the production of a synthesis gas (syngas) rich in H_2 and CO, which is converted in methanol by a catalytic reform chemical process. The technology evolved a lot in the past few years having achieved acceptable levels of efficiency of conversion and production costs, when the raw material is of fossil origin (natural gas).

Typically, the methanol production process consists of the following phases: (a) gasification of the raw material (in this case biomass); (b) conditioning of the syngas to remove impurities such as tars and methane and to adjust the hydrogen to carbon monoxide ratio, using commercially available technologies; finally, a catalytic reaction at elevated temperatures and pressures to form methanol. The technology for the production of methanol, ammonia, and other chemicals, from the syngas of natural gas and mineral coal, is commercially available. In the past, the European Union bore extensive studies from pilot plants of gasification. In the present economic conditions and considering the feasibility of producing methanol in commercial scale using natural gas as raw material, the biomass option is not receiving much attention.

Table 5.7.2 shows the preliminary results of the economic and energy balances of the production of methanol from biomass, using several technologies already developed for the gasification of this raw material. The analysis considers the costs of production as being viable for commercial gasifiers of coal, and potentially achievable for gasifiers to be developed for biomass. The energy efficiency of the Koppers-Totzek System concepts (K-T), System IGT-RENUGAS® and System BCL (indirect gasification) varies between 49% and 68%. These efficiencies are comparable to the 63% of a typical system based in natural gas and to 48% of the second-generation systems based on coal. The efficiency of conversion of the carbon reflects the relative proportions H_2 to CO of the raw material and varies from 33% for a Koppers-Totzek (K-T) system based on biomass to 79% for a system based on natural gas.

Table 5.7.2a Energetic and Economic Balance of the Methanol Production from Several Raw Materials and Different Technologies

Process	Biomass Koppers-Totzek (K-T),	Biomass IGT-RENUGAS®	Biomass BCL (indirect gasification)	Natural Gas	Mineral Coal
Tons MeOH/day	790	920	1,110	2,500	5,000
Tons of feedstock/ton MeOH	2.30	1.97	1.63	0.64	1.76
Low Heating Value of feedstock, GJ/ton	18.87	18.87	18.87	52.25	24.75
MeOH, LHV, GJ/ton[a]	21.14	21.14	21.14	21.14	21.14
Energetic Efficiency, %	48.7	56.9	68.4	63.3	48.5
Carbon Utilization, %	32.6	38.0	45.9	79.2	ND

ND – not determined
[a] methanol vapor
Source: FAAIJ, et. al., 1999

Previous analyses have shown that for a 400 MWth plant based in biomass costing US$ 12/bOE, the following results were obtained: US$ 75-93/bOE of methanol, with efficiency varying from 54 to 58% (1995). These costs are not competitive with the production of methanol from natural gas, whose costs are around US$ 56/bOE of methanol. This analysis indicates that the final cost of the biomass has a significant influence in the end cost of the bio-methanol of approx. 30%. Other analyses have shown that the main factor in the energy cost of bio-methanol is not the final cost of biomass but the processing cost. The final costs are distributed as follows: 15% for the biomass, 60% for conversion, and 24% for transportation and distribution. Other cost estimates show that, considering the costs of the biomass [varying in the range US$ 7-6/bOE (based in the eucalyptus value), and the costs of logistics, conversion and distribution, for today's and near future conditions (2010 to 2015)], the final costs would be US$ 75/bOE - US$ 62/bOE of methanol, respectively. Table 5.7.2b shows the main advanced concepts for the production of methanol from syngas obtained by the gasification of biomass.

Table 5.7.2b. Main Advanced Concepts for the Production of Methanol from Biomass

Concept	Gas cleaning	Reforming Technology	MeOH synthesis technology process	Power generation	Output, MW		Net energy efficiency, % (HHV basis)*
					Fuel (HHV basis)	Net electricity	
IGT-max H_2 MeOH + power	Quench	No	LPMeOH	Combined cycles	149	36	43
IGT MeOH + power	Hot (450°C) advanced technology	CAR	LPMeOH (with steam addition)	Combined cycles	179	41	51
IGT MeOH + power	Quench	No	LPMeOH (with steam addition)	Combined cycles	114	84	46
BCL MeOH + power	Quench	SMR	LPMeOH (with steam addition) and CO recycle	Steam Cycles	262	-15 (input)	58
IGT MeOH only	Hot (450°C) advanced technology	CAR	GPMeOH (Gas phase)	Steam Cycles	207	12	51
BCL MeOH only	Quench	SMR	GPMeOH (Gas phase)	Steam Cycles	254	-15 (input)	55

*Performance calculations: 427 MWth biomass input (HHV basis with 30% moisture content. Only 427 MWth biomass is taken as input (the electricity input is subtracted from the fuel (MeOH) output:
LPMeOH – liquid phases MeOH process;
IGT – Institute of Gas Technology - RENUGAS® Technology – pressurized gasification using oxygen as oxidant. This concept produce medium calorific value of gas;
BCL Technology – the indirect gasification concept developed at the Batelle Columbus Laboratories. This concept produce medium calorific value of gas;
CAR – Catalytic Auto thermal Reforming (oxygen is necessary);
SMR – Steam Reforming.
Source: FAAIJ, et. al., 1999

To improve efficiency and decrease costs, R&D priorities should include: auto thermal catalytic reform, technology for production of methanol in liquid phase-LPMEOH, improvement of the processes based in the shift reactions or new shift catalytic technologies, improvement of the syngas cleaning processes, development of the concept of obtaining bio-fuels and electric energy in combined cycles (the combined production of bio-fuels and electricity should reduce the global costs with the increase of the thermodynamic global efficiency of the units). These estimates reveal that higher conversion efficiencies and lower capital costs that would follow the increase of scale of the production units, and would have a significant effect in the use of the energy and the costs associated with the transport of biomass.

AIII-5.7.3 Market perspective for methanol

Today the main application foreseen for methanol is as transportation fuel through its use in vehicle fuel cells, with high conversion efficiencies (2 to 3 times the thermodynamic efficiency of the internal combustion engines), and low environmental pollution emission levels. Other applications for methanol are in the condition of mixtures with other fossil or biomass fuels, for instance, diesel and the bio-oil, which are being tested in motors for the generation of electric energy, and in the process of transesterification of vegetable oils to convert them in biodiesel.

AIII-5. 8 Flex-Fuel Vehicles

AIII-5.10.1 AIII-5.8.1 Introduction

The "Flex-Fuel" concept originated from research carried out in the United States, Europe, and Japan in the late 1980s. The research was aimed at solving the problem of lack of a distribution and supply infrastructure for methanol and ethanol.

In 1988, a United States law (the "Alternate Automotive Fuels Act") encouraged the development of flex-fuel technology, allowing the use of alcohol-gasoline blends consisting of up to 85% alcohol. This limit was established with the objective of assisting during "cold starts". In the US, the issue regarding "cold starts" was handed over to fuel suppliers, which resulted in the establishment of this 85% upper % limit for alcohol. In Brazil, the same issue was the responsibility of the automobile industry that designed a cold-ignition auxiliary system.

This Flex-fuel technology was based on analyzing alcohol content in the blend with sensors and on the computerized adjustment of engine operation to the most favorable conditions for the blend. US flex-fuel technology involved a pre-engine sensor, which was expensive and somewhat problematic.

In 1992, General Motors introduced the "Flex-Fuel" technology in the United States. Soon, other manufacturers followed offering products with similar characteristics, mainly aimed at commercial fleets. Currently, it is estimated that more than 3 million such vehicles exist in the United States.

Research done in Brazil resulted in a technological conception that was superior to the existing American flexible system. The Brazilian version included a "lambda emission sensor" (NOTE: please explain this term) to measure the oxygen concentration in the exhaust gas and the computerized adjustment of an optimum setting in a complex exhaust gas database for oxygenated mixtures. The entire process takes around 13 seconds to adjust the engine setting after fuel change. Fuel injection systems and existing knowledge on ethanol-running engines made the task much simpler for the Brazilian industry. In addition, the Brazilian "Flex-Fuel" concept proved to be better in terms of performance and fuel savings, besides allowing the use of up to 100% hydrous ethanol or any ethanol-gasoline mixture. For this reason, Volkswagen, which launched the first of this kind in 2003, adopted the name of "Total-Flex", making a comparison statement regarding the prior limited American "Flex-

Fuel" technology. Table 5.8.1a indicates the current state of the domestic light vehicle fleet and projections for 2010 and estimated participation of the FFVs.

Table 5.8.1a Projections for Light Vehicles Fleet in Brazil and estimated market participation of Flex-fuel vehicles

Year	Gasoline[1]	Ethanol [2]	Flex-Fuel	Total	Flex-Fuel
(in millions of vehicles)					(%)
2002	14.68	2.72	0.00	17.41	0
2003	15.41	2.45	0.05	17.91	0.3
2004	16.05	2.15	0.30	18.49	1.6
2005	16.54	1.81	0.75	19.10	3.9
2006	16.73	1.48	1.56	19.77	7.9
2007	16.62	1.18	2.69	20.48	13.1
2008	16.47	0.93	3.86	21.26	18.2
2009	16.30	0.73	5.07	22.09	22.9
2010	16.09	0.56	6.32	22.97	27.5

[1] Gasohol blend: 25% anhydrous ethanol and 75% gasoline
[2] 100% Hydrous Ethanol
Source: Copersucar (2004)

Most of the emissions problems posed by the flexible blends were solved with the approximation of the cat system, bringing it closer to the emission source to compensate for the temperature differences in the mixture. The cat-device is optimized for 100% gasoline emissions, in this case, the worst-case scenario.

In Brazil, Bosch undertook the earliest studies for the application of this technology in 1991 aimed at the possibility of "Flex-Fuel" vehicles replacing the 100% ethanol fleet. At that time, ethanol-powered vehicles were undergoing a sharp decline in sales.

Supporters of this innovative technology claimed that, although having an extensive alcohol supply infrastructure, Brazilians expected further guarantees in terms of supply. Brazilian consumers went through fuel shortages in the late 1980s and sought flexibility to choose what fuel to use. Under this scenario, an attractiveness and differentiation factor would be introduced in the market. It would also represent savings for carmakers, which would no longer need to develop two simultaneous fuel systems, one for ethanol and another for gasoline vehicles. In addition, in the eyes of automakers, it would represent greater flexibility for ethanol producers in supplying their fuel during seasonal harvest variations, in supplying the international sugar market, and in a potential creation of an international market for the ethanol (USA, EU, Japan, South Korea, and India).

Currently, the Brazilian "gasohol" blend includes 25% anhydrous ethanol and 75% gasoline. Since hydrous ethanol allows around 4.5% v/v (or 7% w/w) of water, mixing it with the gasohol blend could trigger the separation of the water phase. However, if the blend were composed of 20% to 25% anhydrous ethanol, phase separation would occur only under temperatures below minus 6 degrees Celsius (-6 °C) (a rather improbable scenario within most of the Brazilian territory). In 2002, Ford introduces a "Flex-Fuel" prototype, triggering growing interest, and leading to new incentives to expand the use of ethanol. Finally, in August 2002, the IPI[22] tax reclassification for vehicles allowed "Flex-Fuel" vehicles to receive the same fiscal treatment as 100% alcohol vehicles.This news and the increasing interest in the use of ethanol by other countries (e.g. US, EU, Japan, South Korea, India, China, Thailand and Australia), stimulated the Brazilian growing automobile industry's interest in turning the country into a production center for "Flex-Fuel" vehicles.

The "Flex-Fuel" advent represents a new milestone in the successful Brazilian experience with the use of ethanol and opportunities to export both the fuel and the technology (mainly to the MercoSur Economic Community).

AIII-5.10.2 AIII-5.8.2 Flex-fuel engine conception

A hydrous-ethanol-running vehicle should not be directly compared to a Flex-fuel one. Because they are based on entirely different fueling concepts, distinctions should be made and considered. An ethanol-running engine is designed for an optimum performance when hydrous ethanol is being used. Likewise, a gasoline-running engine in Brazil is designed for an optimal performance for the standardized blended fuel (22% anhydrous ethanol + 78% gasoline). In contrast, Flex-fuel vehicles are intended to offer flexibility enabling the driver to use whatever is best at a specific scenario (fuel price, fuel availability, performance need, mileage need, etc.). Flex-Fuel vehicles are designed to run with two different fuels, which have different characteristics, and, therefore, cannot be optimized for both fuels. Improvements are being made increasing the engine efficiency.

AIII-5.10.3 AIII-5.8.3 Perspectives for flex-fuel technology in the world

With the availability of flex-fuel vehicles globally likely to rise, the appeal for cheaper fuel in overseas markets would be expected to increase (Table 5.7.2b). This tendency would further intensify, if, as expected, Russia signs the Kyoto Protocol validating it. Participating developed countries become even more concerned to find ways of reducing their carbon emissions, and, others, such as Brazil, anxiously wait for the emergence of a promising ethanol international market.

[22] IPI: Taxation on Industrialized Products.

GAS FUEL

AIII-5. 9 Production of hydrogen via reformation of ethanol

AIII-5.9.1 Introduction

A close examination of recent literature illustrates the enormous efforts being channelled to the production of hydrogen from various sources.

Examining the related literature being made available for the past few years, it becomes evident the remarkable effort and great expectation regarding the role of hydrogen in the future energy matrix. The use of hydrogen in diverse energy systems (i.e. mobile and stationary) is for the most part associated to fuel cells.

In addition to activities being developed by the private sector (multinationals corporations devoting substantial investments to research activities), some global strategies for hydrogen utilization are being implemented e.g. the Clean Urban Transport for Europe (CUTE) program, a public-private initiative established in 2001, is an example of such strategies. Another example is the International Partnership for the Hydrogen Economy (IPHE), which was created in 2003. Studies that provide the basis for these initiatives, suggest an increasing hydrogen participation in the international energy matrix for 2010. This can be envisaged taking into consideration the role assumed by hydrogen during the second half of the 20th Century. (But there are many obstacles to be overcome)

The production of hydrogen, which is a secondary[23] source of energy, generally involves the use of one or more substances containing hydrogen, and the utilization of a primary source of energy. Usually, electricity or heat is used as the primary source of energy in order to separate hydrogen from other elements. There are already well developed technologies for the main known processes, and still under development seeking new materials, new techniques and, economic feasibility. Among the substances utilized for the generation of hydrogen, organic substances play an important role mostly due to the amount of hydrogen present in them. Fossils and biomass fuels (direct products: wood, ethanol, etc.; residues: biogas, shells, straws, etc.) are a very important source of hydrogen.

AIII-5.9.2 Production of hydrogen from reforming ethanol from sugarcane

Among the available alternatives for the production of hydrogen, the use of ethanol from biomass is a particularly interesting option for countries with a strong agricultural potential and tradition as is the case of Brazil. The hydrogen generation process through the reform of vapor-alcohols is well understood, especially with the utilization of methanol, which is

[23] **Secondary source of energy: energy source not freely available in Nature, requiring a primary source of energy to be produced.**

widely available. Recently, studies on the use of the ethanol in the production of hydrogen are becoming increasingly available. In most cases, they involve the development of catalysts for this reaction (metallic mixtures based on Cu, Ni or Cr supported in gamma-alumina, for instance), trying to maximize the conversion of ethanol into hydrogen. Presently, this process is not commercially available. It is expected that by 2010 a complete system with acceptable conversion efficiency (above 80%) will be available.

The main process for hydrogen production from ethanol involves its reform by steam consisting in reacting ethanol and water, in the form of vapor. Ethanol is soluble in water and the two substances do not react under standard conditions. High temperatures (reaction endothermic around 600 °C) and catalysts are necessary to induce a reaction in an efficient way. The following exemplifies the occurring reactions:

- $C_2H_5OH + 3H_2O <> 6H_2 + 2CO_2$
- $CO_2 + 4H_2 <> CH_4 + 2H_2O$
- $CO_2 + H_2 <> CO + H_2O$

From the reform reactor, a mixture of gases called "gas synthesis"[24] or "syngas" is obtained. The mixture then goes through two additional reactors, which convert CH_4 and CO into CO_2 and hydrogen (*shifting reactions*). Finally, columns of purification remove residues from contaminant gases, mainly CO (as it is the case on the use of hydrogen in membrane of solid polymer fuel cells), resulting in hydrogen with the necessary purity to the utilization sought. Carbon dioxide gas produced during the process is vented out into the atmosphere, therefore releasing the CO_2 absorbed during the sugarcane crop growing.

Since the *shifting reactions* are well understood and reactors bearing this technology are commercially available, R&DD is concentrated in catalysts for the ethanol reform. Presently, several institutions are looking for more economical and efficient catalysts, involving a range of alloys and mixtures of elements (usually metallic). Several patents have already been secured. Besides catalysts, the topologies of reform reactors have developed towards more efficient and compact systems, characteristics which are extremely necessary for the application of reformers on vehicles.

Among the alternatives considered, auto-thermal reactors present a greater challenge in view of complexities involved in the control of chemical reactants admission. Companies utilizing H_2 as a fuel have demonstrated interest in alternative processes for obtaining hydrogen, involving the use of water electrolysers, fossil hydrocarbons reformers, acquiring industrialized gases, etc.

Therefore, given the range of catalysts and reactors currently under development (with several patents pending), it is expected that by the end of this decade some combinations of these technologies will be consolidated, resulting in the availability of commercial converter systems for ethanol-based hydrogen.

[24] **Gas of synthesis: composed essentially by the H_2, CO_2, CH_4 and CO.**

The size and quantity of these systems will depend on the degree of success of existing hydrogen programs, prompting ethanol-producing nations to demand the utilization of this technology.

I. *AIII-5.9.3. Conclusions*

Among existing hydrogen research programs, a special attention should be paid to the study of catalysts, which includes the identification of superior materials aimed at reforming processes. In addition, special attention ought to be given to research groups in the area of energy systems, whose objective is the development of semi-industrial prototypes with currently available technologies.

AIII-5. 10 Landfill gas and energy production

AIII-5.11.1 AIII-5.10.1 Introduction

Possibly, one of the most important benefit of Landfill Gas (LFG) energy projects is the ultimate reduction of methane emissions and, consequently promoting the development of cost-effective and environmentally friendly energy.

Landfill waste sites can be compared to large-scale anaerobic digesters, where bacteria prosper in the absence of oxygen. A large proportion of municipal landfills is composed of organic material, which decomposes by bacteria to produce landfill gas (LFG), a mixture of methane, carbon dioxide, and solid residues.

It is very important to capture and use LFG because the environmental and energy benefits this represents. LFG can be used as an economic fuel to generate heat and electricity, allowing commercial exploitation 2-3 years after the completion of the site for a period of 10 to 15 years. The alternative is to allow LFG to escape into the atmosphere causing environmental hazards, air pollution, and global warming[25].

LFG can be used to fuel electricity-generation equipment (reciprocating engines, combustion turbines, fuel cells, or microturbines) *in situ*. Electricity is then transmitted to local electricity grids or directed to end-users. The most common technology for electricity is the reciprocating or combustion turbine. In general, reciprocating engines have proven to be the most cost-effective and reliable technology for electricity from landfill gas, especially for moderately sized projects. Gas turbines are an option for landfill gas projects that can support generation capacity of at least 3 to 5 MW. In addition, several facilities are using micro-turbines and fuel cells for landfill gas applications.

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25 Greenhouse gases (GHG) cause global warming by absorbing infrared radiation in the atmosphere. GHGs include, but are not limited to, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrochlorofluorocarbons (HCFCs), ozone (O_3), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).

AIII-5.11.2 AIII-5.10.2 Environmental benefits

LFG Projects will ultimately destroy methane and other organic compounds in LFG. Each 1 MW of electricity generated by LFG is equivalent to planting approximately 4,800 ha/yr of trees, removing the emissions of about 8,800 cars per year, or preventing the annual use of around 93,000 barrels of oil per year. Additionally, LFG projects will offset the use of non-renewable resources (coal, oil, gas) reducing emissions as illustrated in Figure 5.10.2.

SO_2 → that contributes to the formation of acid rain;
NO_x → that contributes to ozone formation and smog;
Polluting agents → that cause respiratory health concerns; and
CO_2 → a global warming gas

LFG is composed of approximately:
50% methane
45% carbon dioxide
5% non-methane organic compounds (NMOCs)

Gas components contributing to global warming include:

11%	CFCs/PFCs
5%	H_2O
66%	CO_2
18%	Methane

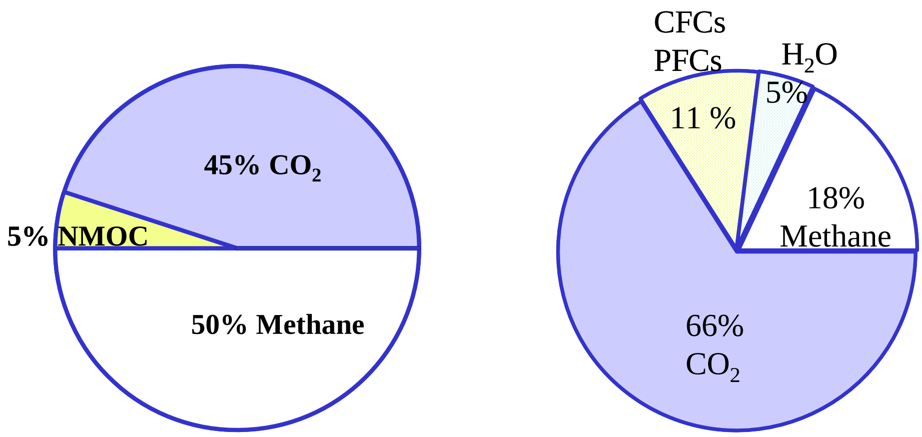

Figure 5.10.2 Distribution of GHG

AIII-5.11.3 AIII-5.10.3 Economics

There are many ways to beneficially utilize LFG. Available niche technologies range from benchmark research, pilot units, and development stage installations to full commercial systems. Technologies exist for low and high volumes of LFG production. Selection of technology is project specific.

Selection criteria include mainly:

- environmental impacts.
- performance.

- reliability.
- accuracy of assumptions;
- regulatory and permitting issues;
- emissions control, and, very importantly;
- project economics.

According to the World Resources Institute, the 15-year average revenue required for a 5MW LFG-to-electricity project without any advantaged cost structure can range from US$44/MWh to US$48/MWh. Changes in one or more elements of operating cost can easily change the revenue required to support the project. Compared to fossil fuel generating facilities, LFG-to-electricity projects have a significant fuel cost advantage. The cost of LFG to an electric generator from landfill sites ranges from US$0.20/million Btu (US$0.19/GJ) to US$0.40/million Btu (US$0.38/GJ) versus US$1.20/million Btu (US$1.14/GJ) for coal or US$3/million Btu (US$2.84/GJ) to US$4/million Btu (US$3.79/GJ) for natural gas.

However, the fuel cost advantage provided by LGF, will be more than offset by the combined higher capital cost (opportunity costs of US$/kW of installed capacity), higher operating and maintenance costs common to small-scale electric energy generation projects. For this reason, fiscal incentives or other forms of credits are essential to mitigate the gap between the market price of generation and the higher cost of generation from LFG.

According to the World Resources Institute and the EPA Landfill Methane Outreach Program, other issues may contribute to this price gap, including:

- Transmission Toll: the buyer and/or supplier must coordinate and pay to deliver the generated electricity to a regional wholesaler or to the power market at transmission-level voltage;
- Integration: the cost to integrate bulk power into the wholesale marketplace (sell and schedule) is relatively fixed and independent of the number of megawatts transacted. The small and atypically sized 3 MW to 5 MW output common to many LFG projects is more costly to integrate on a unit basis than conventional electricity transactions, which are generally made in 50 MW blocks. Under some scenarios, allowing incentives for transmission may ultimately be the viability factor for a LFG project;
- Unit-Contingent Pricing: the electricity generated by LFG facilities is often commercialized as a *unit-contingent product*, as opposed to the more commonly traded, financially firm products that provide liquidated damages in the event of non-delivery. Unit-contingent products typically are sold at a discount since they leave the energy buyer vulnerable to *spot market pricing* during those times the LFG facility, for any reason, is not supplying electricity. Ultimately, the gap between the *cost of energy* from LFG project (fuel or electricity) and a consumer's alternative will determine project viability. Project scale, capital costs relative to the amount of energy delivered, and applicable incentives to pay down capital costs are crucial determinants in the cost of any LFG project. Incentives, particularly for electricity generation, are important in promoting the development of LFG projects.

AIII-5.11.4 AIII-5.10.4 International LFG projects

Established in 1994, the US Environmental Protection Agency (EPA) Landfill Methane Outreach Program (LMOP) is aimed at promoting LFG recovery and utilization within the U.S. and abroad. Promoting international LFG projects through education and technical assistance services helps in the identification of project development opportunities, both in the host country and for American developers, in addition to promoting the benefits of LFG utilization. This is an example to be followed by some developing countries, which already possess the expertise (companies, consultants, etc.), the technology, and the means to promote development of LFG projects in other countries.

In the United States, there are approximately 340 LFG operational projects producing annually around 8 million MWh. According to the US EPA, the country has at least 100 LFG projects currently under construction. The agency indicates that there are over 600 candidate landfills with an estimated potential of over 1,700 MW. Ecologically, this would represent over 8 million hectares of forest, or removing the emissions from over 14.6 million cars on the road, or powering over 1 million homes per year. Despite the expansion of the global waste-to-energy (WTE) industry in the past decade, hundreds of millions of tons of municipal solid wastes still end up in landfills. For every ton of waste landfilled, greenhouse gas emissions in the form of carbon dioxide equivalent increase by at least 1.3 tons. Tables 5.10.4.a,b and c indicate some waste management and related energy generation numbers.

Table 5.10.4a. Reported waste to energy capacity in Europe

Country	tons/year (in 1999)	Kg/capita	Thermal energy (bOE)	Electric energy (bOE)
Austria	450	56	488,480	21
Denmark	2,562,000	477	1,686,880	555,520
France	10,984,000	180	5,168,480	346,240
Germany	12,853,000	157	4,350,400	1,926,720
Hungary	352	6	0.32	64
Italy	2,169,000	137	536,640	374,080
Netherlands	4,818,000	482	0	1,460,800
Norway	220	49	225,440	4
Portugal	322	32	0,16	89
Spain	1,039,000	26	0	309,440
Sweden	2,005,000	225	3,679,360	697,600
Switzerland	1,636,000	164	1,391,680	369,760
UK	1,074,000	18	0,16	303,200
Total reported	40,484,000	154.5	17,528,000	6,521,760

*Table 5.10.4b Sources of Renewable Energy for Electricity Generation**

Sources	**Total (in Megawatts)**	**Renewable Market (%)**
Geothermal	2,793	16%
Biomass	10,120	58%
Solar	387	2%
Wind	4,062	24%
Total Renewable Energy	17,362	2%
Total (Renewable & Non-renewable)	854,655	

* Excluding Conventional Hydroelectric.
Source: WTE (2000)

Table 5.10.4c. Sources of Biomass Energy for Electricity Generation

Biomass	**Total (in Megawatts)**	**Renewable Market (%)**
Wood/Wood Waste	6.23	62%
MSW/Landfill Gas	3.387	34%
Other Biomass	504	4%

Waste-to-energy with 2750 megawatts represents 27% of the biomass category and 0.32% of the entire U.S. electricity generation.
MSW: Municipal Solid Waste
Source: WTE (2000)

AIII-5.10.5 Waste management practices in Brazil

In Brazil, the amount of wastes generated varies from 0.4 kg/person/day to 0.9 kg/person/day. Final disposal and treatment practices around the country include: 60% of MSW disposed at uncontrolled open localities or landfills with some simple form of control, 36% in sanitary landfills, 3% in composting plants, 1% in sorting plants, and 0.4% of the MSW is combusted. Typical recovery of methane or biogas is minimal and there is no regulatory requirement governing this activity. A conservative estimate of 20% recovery of methane gas for passive systems has been considered as the best practice, based on a waste-management industry benchmark and Vega's[26] extrapolation of the results of the latest SITA research into this topic (*Measurement of biogas flow through different final cover at the Montebelluna Landfill – Italy –* SITA/INERIS – Dec/2001). A new waste management policy ("*National Policy for Solid Waste*") has been under discussion for many years but currently no changes are anticipated to the existing

26 **VEGA Bahia Tratamento de Resíduos S.A.**

national policy. There is, therefore, no national framework governing landfill practices and only technical norms issued by the Brazilian Association of Technical Norms (ABNT).

AII-5.10.6 The Brazilian Bandeirantes project

Recently, an international consortium formed by ARCADIS, an international consultancy and engineering company, concluded the development of the largest landfill-gas energy plant in the world. The landfill gas is extracted from the 139 hectares Bandeirantes landfill near Sao Paulo city in Brazil.

This landfill is now used to supply a newly built 23 MW energy plant. As of now (2004), the plant generates 170,000 MWh/yr, sufficient to power more than 58,000 Brazilian households.

The Bandeirantes project has been developed by ARCADIS Logos, the Brazilian subsidiary of ARCADIS together with co-shareholder Van der Wiel Stortgas BV and the Brazilian company Heleno & Fonseca. These three companies formed the joint venture “BIOGAS” which is responsible for the extraction of the gas. BIOGAS has invested R$ 12 million (EUR 3.5 million) in this project and delivers the gas to the power plant, which is managed by a consortium under the guidance of UNIBANCO bank. The gas delivery is based on a 12-year contract that is valued at R$ 100 million (EUR 32 million).

The methane gas from the landfill is hazardous to the environment and contributes to global warming. Based on the Kyoto Protocol, the joint venture will benefit from "carbon credits" (CDMs). A part of this will be used to finance the improvement of the area around the landfill as a compensation for the nuisance from the landfill that the local people have been confronted with.

The energy plant was built (engineering, hydraulics and electricity) in a record time of 3 months by Sotreq, which provided and installed 24 Caterpillar group generators. Sotreq will be responsible for operations and maintenance until 2007, with the possibility of extending the operation contract for an additional 7-year period.

ADIS Logos and Heleno & Fonseca previously have gained the concession for the extraction of the gas. Van der Wiel Stortgas BV has been asked to participate because of the experience they have in gas extraction. ARCADIS Logos designed the gas project, is responsible for the project management and for the development of the energy plant. Table 5.10.6 summarizes plant data of the Bandeirantes Project.

Table 5.10.6 Bandeirantes Biogas Plant Overview

Developed by:	Consortium BIOGAS: ARCADIS Van der Wiel Stortgas BV Heleno Fonseca Construtora técnica.
Launch:	Jan./23/2004
Installed Capacity:	23 MW
Production Capacity:	170,000 MWh annually
Total Cost:	US$ 17 million
Construction Period:	Three months
Operation and Maintenance:	Sotreq: Construction, hydraulic and electrical Project. 24 Caterpillar Generator Groups (up to 12,000 m^3/h of biochemical gas – minimum of 50% methane).

Source: SOTREQ (2004)

ELECTRICITY AND PROCESS HEAT

AIII-5. 11 Electricity generation from sugarcane residues

AIII-5.11.5 AIII-5.11.1 Introduction

The estimated world installed capacity of biomass power plants exceeds 50GW. In 2002, the world electricity generation was estimated at 14,900 TWh. Electricity generated from biomass for the same year was estimated at around 197 TWh (1.3%). Based on 2020 projections, it is estimated that total world energy generation will be 26,100 TWh. 335 TWh of this total will be generated from biomass sources (1.3%). In Latin America (LA), according to 2000 estimations, the total electricity generated was 974 TWh. From this, 11 TWh were generated from biomass. The Brazilian Energy Balance (MME, 2003) shows that in 2000, 349 TWh of electricity were generated in Brazil representing 36% of Latin America total generation.

If these figures are taken seriously they seem to imply that biomass is expected to remain a small player in the energy generation business in the world, including Latin America. Nonetheless, the scenario may prove to be quite different in Brazil. The reason for this is the size of the pulp/paper and sugar/ethanol industries, and their tradition in cogeneration of heat and electric power to meet their own requirements. The existence of large biomass resources (around 6.5 million ha of planted forests and 5.3 million ha of sugarcane) and an installed capacity for cogeneration in the order of 2,400 MW (ANEEL, 2003), seems to indicate a bright future for both sectors, which may become major players in the area of electricity generation from renewable sources.

Following is a description of the sugarcane industry in Brazil and its potential contribution to the country's electricity demand.

AIII-5.13.1 AIII-5.11.2 General background

Sugarcane is cultivated in more than 100 countries around the world. In Brazil, it has been uninterruptedly cultivated since the 17th century. Brazil produces approximately 350 million tons of sugarcane annually, representing more than a quarter of the total world production. Sugarcane processing requires large amounts of energy, the average values being: 12 kWh of electric energy; 16 kWh of mechanical energy; and 330 kWh of thermal energy per ton of sugarcane processed. Fortunately bagasse[27] provides all the needed energy. If sugarcane were to be considered as a primary energy source, each ton of stalks would contain, on the average, 150 kg of sugar, 140 kg of fiber (dry matter), and, associated with each ton of stalks, approximately

27 Bagasse: the sugarcane plant residue left after a product, in this case juice, has been extracted.

140 kg of fiber (dry mater) in leaves. This biomass portfolio represents energy content of approximately 7.3 GJ or 1.17 bOE. Yet, there is opportunity for improvements. Presently, this potential is very inefficiently used mostly because leaves are usually burned during pre-harvesting activities in order to facilitate harvesting. In contrast, more than 90% of the generated *bagasse* is burned in the boilers to supply energy demands of the industrial process. Table 5.11.2 shows the potential availability of sugarcane residues and their energy value for the World and Brazil

Table 5.11.2. Worldwide estimates of sugarcane residues

Residues	World (million ton)	Brazil (million ton)
Sugarcane production	1,300	350
Bagasse[1]	360	100
Trash[1] (tops and leaves)	360	100
Total biomass	720	200
Millions of barrels of oil equivalent[2]	1,050	280

[1] 50% moisture content
[2] Higher heating value basis
Source: UNICA, 2003; COPERSUCAR, 2004; and FAO, 2003

The fact that sugarcane mills generate the electric power they need (self-sufficiency) makes them potential candidates to become sellers of energy surpluses to the grid. This is common in places where traditional energy sources have become expensive (e.g. dependence on imported liquid fuels), such as in the islands of Mauritius, Reunion, Hawaii, Guadeloupe, and in Guatemala. Since generated *bagasse* is just sufficient for cogeneration during the crushing season (approximately six months), a supplemental fuel source has to be made available for off-season generation. Fuel oil is used in Guatemala and Hawaii, and coal in Mauritius, Guadeloupe, and Reunion.

During 2002, a total of 746 GWh was injected in the Mauritius' national grid, representing 43.5% of the island generation. From this total, 299 GWh came from *bagasse* and the balance came from coal (DEEPCHAND, 2003).

In India and Brazil, sugar mills are becoming important supplier of electricity be it mostly during the harvesting season. In India, several states are passing regulations to promote renewable power generation from sugarcane by providing special financing incentives to investors. In 2003, a national program to motivate the penetration of renewable and alternative sources of electric energy was established in Brazil – the Program of Incentive to Alternative Sources (PROINFA). The PROINFA was regulated and approved by the Brazilian Congress early in 2004, and calls for bids are in progress. It is worth mentioning that over 90% of the electricity generated in Brazil comes from hydroelectric power plants, and, conveniently, the dry season is concurrent with the sugarcane harvesting period in such way that the energy provided by the mills helps the hydroelectric generating system pass though this period where reservoir levels are usually low.

Today, it is estimated that the total installed power capacity in the sugar/ethanol mills in Brazil exceeds 2100 MW, from which 1500 MW are used for internal consumption and around 600 MW are exported to the grid (UNICA, 2004). CPFL (Companhia Paulista de Força e Luz), an important power utility in the State of São Paulo, purchased 1250 GWh from the mills in its concession area, in 2003.

AIII-5.13.2 AIII-5.11.3 The Brazilian scenario

In just few decades, Brazilian sugar and ethanol industry evolved from total dependency from public utilities[28] to total self-sufficiency, during the harvesting season. The motivation was the increase in electricity costs and the necessity to modernize their energy sector, mainly the boilers; the old boilers with steam pressure in the range of 10-15 bar were replaced by boilers with pressures of 22 bar and above. At 22 bar/300°C steam conditions, the mills became self sufficient in electric, mechanical and thermal energy using *bagasse* as the only fuel (MME 2003). Table 5.11.3 shows the present situation of the energy section in the Mill.

Table 5.11.3 Average Conditions at the Majority of the Brazilian Sugar/Ethanol Mills

Steam conditions	22 bar/300°C
Electric energy consumption	12 kWh/ton cane
Mechanical energy consumption	16 kWh/ton cane
Thermal energy consumption	330 kWh/ton cane
Boiler efficiency	78 %
Purchased electric energy	Zero
Surplus *bagasse*	7%

Sources: Copersucar, 2004

With the privatization of most Brazilian power utilities, the regulation of Independent Power Producers (IPP) and the opening of the transmission and distribution network to every participant of the electric power market, created a favourable scenario for IPP's to sell their electricity. In 1999, several ethanol/sugar mills were motivated to optimize their industrial processes making their plants more efficient, allowing the generation of power surpluses that could be sold into the grid. This process also included the replacement of the older boilers by

28 Public utility: a business organization, such as an electric company, performing a public service and subject to special governmental regulation.

new high-pressure boilers with steam pressure in the range of 65 to 82 bar and efficiency around 85%. There are approximately 30 mills generating around 600 MW of excess power.

The PROINFA has created a market share for three types of renewable energy: small hydro (<30MW), biomass, and wind power. This program has two phases:

- Phase 1 (until 12/2006): 3.300MW equally divided among three alternatives
- Phase 2 (after 2006): 10% of new capacity shall be supplied by the three sources.

Other renewable energy sources (e.g. solar) can be incorporated into the PROINFA in the near future, as they become competitive.

Reference prices were established for each energy source ranging from R$ 93.77 (US$ 32) per MWh for biomass, to R$ 204.35 (US$ 70) per MWh for wind power. ELETROBRAS [29] will guarantee a power-purchasing contract for 20 years.

AIII-5.13.3 AIII-5.11-4 Alternatives to increase power surpluses

The prevailing technology for power generation in sugar/ethanol mills, involves the firing of *bagasse* into boilers with steam conditions at 22 bar/300°C and backpressure turbine-generators exhausting steam at 2.5 bar/saturated (100% cogeneration mode). The maximum surplus power that can be obtained with the optimization of this bagasse system is 10 kWh/ton cane. With *bagasse*-fired boilers at 82 bar/ 480°C steam conditions, surpluses can be increased to around 50 kWh/ton cane. In both situations, the only fuel will be *bagasse*, and the power generating system will operate in 100% cogeneration mode during the harvesting season only.

If extraction/condensing turbine generators are used, and process steam consumption is reduced to the 350 kg of steam/ton of cane level, the excess electricity generation can reach values close to 70 kWh/ton of cane.

In order to extend power generation beyond the harvesting season, two initiatives will be required:

- reduction of process heat consumption from the current 300 kWh/ton cane. 230kWh/ton cane seems to be a reasonable value if existing mechanical drives are to be maintained;
- a supplemental fuel to *bagasse* must be provided. It has been suggested that sugarcane trash[30] could be used.

With steam pressure at 82 bar/480°C, or higher, process thermal energy consumption at the 230 kWh/ton cane level, and partial recovery of the sugarcane trash, the surplus power potential can

29 ELETROBRAS: the holding of all Government Utilities in Brazil.
30 The recovery of sugarcane trash (now just burned at the field before harvesting) could improve the amount of biomass available at the mill site

be improved to approximately 150 kWh/ton cane. As a reference, this potential is nearly equal to the monthly average consumption of a household in Brazil – that is, each ton of sugarcane processed at the mill provides surplus power in an amount sufficient to meet the needs of an average Brazilian home during one month.

A technological innovation, still under development, can nearly double this potential in the near future – biomass integrated gasification with gas turbine (BIG/GT). Instead of burning sugarcane residues directly in the steam boilers, this technology allows residues to be gasified. The resulting gas adequately cleaned, is then fired in a gas turbine that drives an electric generator. The hot gas from the turbine goes to a heat-recovery steam generator (HRSG) where high-pressure steam is produced and used to drive a steam turbine-generator. The total surplus power potential of this technology is around 300 kWh/tonne of cane (LARSON et al., 2001).

Table 5.11.4 Alternatives for Surplus Power Generation

Technology	Operation	Process Heat kWh/tc	Surplus Power kWh/tc	Brazil's Potential		% Brazil´s Consumption
				GWh	MW	
22 bar/300°C backpressure TG	Season	330	0-10	3 500	800	1
82 bar/480°C backpressure TG	Season	330	40-60	21 000	5 200	6
82 bar/480° extraction/ condensing TG	Year round	230	100-150	52 500	7 000	15
BIG/GT	Year round	< 230	200-300	105 000	14 000	30

Source: Copersucar, 2004

AIII-5.13.4 AIII-5.11.5 Economic aspects

The Brazilian heavy equipment industry is internationally competitive; power generation systems can be installed at the mills with total investment costs in the range of US$ 500 to 600/kWe (installed capacity) for backpressure systems, and US$ 600 to 800/kWe for extraction/condensing systems. International competition costs for the latter are around US$ 1,500/kWe, using as references projects in Mauritius, Reunion, and Guadeloupe.

Costs for the BIG/GT technology must be reduced (based on the learning curve) before it can compete with conventional systems. Investment costs for this technology were estimated at US$ 2,500/kWe (GEF Project).

The electric energy generated by the mills is being sold to the power utilities at prices ranging from US$ 30 to 35/MWh, which compares very favorably to sale prices required for natural gas fired combined cycle power plants, estimated to be around US$ 40/MWh.

AIII-5.13.5 AIII-5.11.6 Environmental issues

The electricity generated in the sugarcane mills in Brazil is expected to be displacing electricity produced by thermoelectric plants fueled by natural gas. These plants are expected to be releasing around 500 kg CO_2 equivalent/MWh (Brazil/US Aspen Global Forum, 2000). Therefore, the potential of CO_2 abatement for power plants installed at the sugar/ethanol mills is in the order of 26 million ton/yr (considering that the 150 kWh/ton cane technology is used, and 350 million tons of sugarcane are harvested annually).

At the local level, the stack emissions from the sugar/ethanol mills will not be affected negatively by the surplus power generation since nearly all bagasse is burned in boilers. The trash burning during the off-season will increase the amount of total emissions during the year. The pollutants to be concerned with are particulates and NOx. Since mills are located in the rural areas, these emissions are not expected to cause health problems.

AIII-5. 12 Electricity generation from biomass gasification

AIII-5.12.1 Introduction

Gasification is one of the most important R&D areas in biomass for power generation, as it is the main alternative to direct combustion. Gasification is a thermo-chemical conversion technology where a solid fuel is converted into a combustible gas. The product gas consists of carbon monoxide, carbon dioxide, hydrogen, methane, trace amounts of other hydrocarbons, water nitrogen, and various contaminants (e.g. char particles, ash, tars, etc). The importance of this technology relies in the fact it can take advantage of advanced turbine designs and heat-recovery steam generators to achieve high-energy efficiency.

Gasification technology is not new; the process has been used for almost two centuries e.g. in the 1850s much of London was illuminated by “town gas”, produced from the gasification of coal. This technology is close to commercialisation with over 90 installations and over 60 manufactures around the world. Currently only gasification for heat production has reached commercial status. The best known are the Bioneer, PRM Energy, Foster Wheeler, and Lurgi Umwelt Wen *et al* (1999 fixed-bed, updraft -FBU- type). The main attractions of gasification are:

- higher electrical efficiency e.g. 40% + compared with combustion 26-30%
- the possibility to substantial new developments e.g. advanced gas turbines, fuel cells, etc;
- possible replacement of natural gas or diesel fuel use in industrial boilers and furnaces;
- distributed power generation where power demand is low and;
- displacement of gasoline or diesel in an internal combustion (IC) engine

However, as of today, biomass gasification to generate electricity cannot be considered an economically viable technology. The most significant gasification plants developed so far are power units working within a production range of 1 to 8 MWe. Main technological issues include: operation pressure (atmospheric or pressurized reactors), heating (direct or indirect), bed type (fixed, restricted to small units, and fluidized for higher capacity units) and gasification agent type (air, oxygen, with vapor injection). The current tendency is the utilization of CFB – Circulating Fluidized Bed Units, with atmospheric catalytic reactors and direct gasification working within a production range of 50 to 80 MWe. Beyond this range, pressurized reactors are recommended.

Modern technologies like the BIG/GT-CC (Biomass Integrated Gasifier/ Gas Turbine – Combined Cycles) are expected to increase efficiency and reduce costs over power plants through advanced technologies (Gas turbines/ Special Combustion Chambers) increasing production scale to 150 MWe. Studies on BIG/GT-CC plant with installed capacity of 30 MWe, using wood as feedstock at a cost of US$ 25/bOE, could achieve efficiencies of 41% and 45%, with capital unit cost of US$ 4000/kWe (BLACKADDER, 1992).

Estimates for the 2010 to 2020 period, considering a scenario of technological advancement, plants with capacity of 110 MWe using wood at a cost of US$ 25/bOE, will have a capital unit cost of US$ 1600 to 2400/kWe, and energy production costs of US$ 0.07 to 0.09/ kWh (CGEE, 2003).

However, considering the evolution of biomass costs and technology growth in the sector, forecasts for capital unit cost are: US$ 1500/kWe in 2015; and US$ 1100/kWe in 2030, with energy production costs of US$ 0.04/kWh (CGEE, 2003).

There are various programs underway, worldwide and aiming at improving these technologies to produce electricity from biomass. Technological limitations tend to be overcome in the long run. The US DOE predicts an installed energy production capacity of 18 GWe for 2010 and 100 GWe for 2030. Projections assume the implementation of new technologies, such as the integration of gasification or pyrolysis plants with gas turbines through combined cycles. Consequently, this would lead to a thermodynamic efficiency improvement from 40% to 45%, depending on the plant capacity. It would allow energy production costs to be reduced to US$ 40 - 50/MWh (CGEE, 2003).

AIII-5.14.1 AIII-5.12.2. Gasification technology

Applications for current gasification technologies include: heat and electricity production, and gas production for methanol and hydrogen syntheses. These technologies are essential for heat and energy production in small scale. Technologies for chemical synthesis are still under development.

The primary product resulting from the gasification process is a fuel gas mixture, known as "producer gas", which has to be treated in order to meet requirements for final use.

The efficiency obtained in this process, defined by the fuel gas energy in relation to the organic content of the raw material used in the process, is in fact high, reaching 80% to 85%.

Predictions consider a final efficiency for biomass electricity conversion of 45% with the use of combined cycles (BIG/GT-CC).

AIII-5.12.3 Operating conditions of the gasifier

The type of reactor, pressure and operating temperature, biomass feedstock physical and chemical characteristics, and other operating conditions are all crucial variables within the gasification process.

The gasification process involves the volatilization of biomass and the conversion of the remaining carbonaceous particles into atmospheric air, oxygen, water vapor, or a combination of them, to produce a gas of low or medium heating value.

When air is used as the gasifying agent, the resulting gas has high nitrogen concentrations and low heating value (on dry basis), which is approximately 5 to 6 MJ/Nm^3. However, if oxygen is used instead of air, the heating value of the produced gas can be increased to 13–14 MJ/Nm^3.

Another important variable with direct impact on the performance and economics of biomass gasification systems is the operating pressure of the gasifier. This variable is particularly important in systems that use combined cycles with gas turbines. Pressurized gasifiers produce gas that can be directly fed into the gas turbines, leading to higher global system efficiency. Feeding systems of this type of gasifier is the main technological barrier for the economic application of this process.

AIII-5.12.4 Small scale gasifier (up to 1MWe)

Usually, gasification technologies are aimed at supplying electric energy to small local demands, mainly where offer is limited, costs are high, and biomass is available. Under this scenario, the updraft-stream gasifier technology (fixed bed gasifier) is the most commonly employed system, allowing a maximum electric power of 500 kWe.

AIII-5.14.2 AIII-5.12.5 Biomass integrated gasification systems to gas turbines (BIG-GT)

The development and commercial viability of the BIG-GT is expected to in medium term (10-15 years). Thermal efficiency for a BIG-GT unit will be substantially improved when the enthalpy of the high temperature gas leaving the turbine is used to produce steam in the combined cycle (BIG/GT-CC). Figure 5.12.5 shows the schematics of a plant that employs the BIG/GT-CC technology from atmospheric gasification and direct heating (project being proposed by TPS).

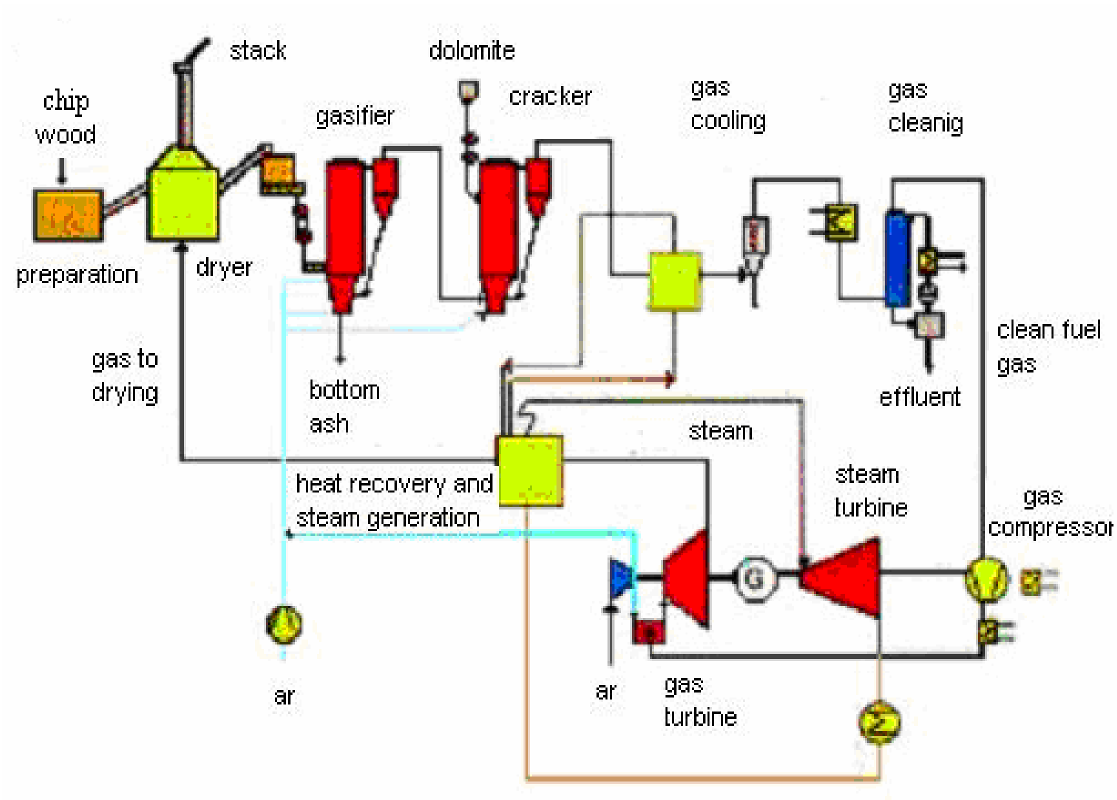

Figure 5.12.5. Power production unit based on the BIG/GT-CC technology (TPS, 2004).

AIII-5.12. 6 Current stated of the BIG-GT technology

Over the past few years, several biomass gasification projects were developed for power generation. Table 5.12.6a summarises the main projects.

The main technologic issues in the demonstration of the BIG-GT technology are basically related with the technology scale-up, the cleaning of the gasification gas, the turbine's adaptation to work with a low heating value gas (gasification gas), and the risks in the supply of biomass at acceptable costs.

AIII-5.12.7 Long term perspectives for the BIG-GT technology

Table 5.12.7 indicates some of the challenges to be overcome in order to make the BIG-GT technology commercially viable in the long run. It has been verified that, in the long run, the most promising ways to increase efficiency and lower the costs for the development of BIG/GT-CC systems, are the technological improvement, the scale-up effects in the economic evaluation of these systems and the actual result of the learning factor.

A long run analysis, approximately 50 years, indicates the following issues: increase efficiency; cost reduction; comprehensive economic evaluation of systems, considering large-scales projects; learning curve issues; etc. These factors will have substantial impacts on the reduction of unit capital costs (LARSON et al., 2001).

AIII-5.12.8 Biomass gasification integrated to internal combustion engines (BGICE)

Electrical production through use abbreviation biomass gasification integrated to internal combustion engines is the commercial technology for small-scale projects, for capacities of 150 kWe. It is expected that larger units will give better economic results. In the EU, there is a special motivation for the use of such systems aimed at the co-generation market, including units with generating capacity of 5 MWth using forestry residues.

AIII-5.12.9 Perspectives on new gasification technologies

The search for new gasification processes that allow the use of a wide variety of feedstock is increasing the hope for the electric generation sector. Recently, an emerging technology named DM1-2 (the Blue Tower technology) came to the spotlight, bringing expectations for 5 MWth capacity plants. This concept is based on the presence of water vapor and indirect heating (allothermal gasifier system process), which allows high levels of hydrogen (around 50%) in the producer gas.

The main characteristics of the producer gas are: CO = 12%; H_2 = 53%, CH_4 = 6%; N_2 = 2%, CO_2 = 25%, C_2 - C_3 = 2%, with a high heating value (HHV) of around 12 MJ/Nm^3.

The main applications for producing gas are electricity generation, production of bio-fuels (methanol, hydrogen, etc.). Bio-fuel can be produced from producer gas due to its synthesis gas nature.

AIII-5.12.10 Liquid fuel and chemical from biomass gasification

Currently, the production of liquid fuels and chemicals by the catalytic conversion of the gasification gas (syngas) through the Fischer-Tropsch (FT) process, is receiving especial attention. The fact is that, although some time ago there was a great interest for the production of methanol, considerations related to the direct impact over humans and the environment, have reduced the space for its use as a source of energy in large scale.

As of now the production of liquid fuels and chemicals through the Fischer-Tropsch technology (Gas-to-Liquid technology or GTL technology) is commercial only for the gasification of coal or with the utilization of natural gas as a feedstock. The SASOL Limited, a company in South Africa, produces 40% of the country's fuel using this technology.

AIII-5.12.11 BIG-GT applications in Brazil

Two projects worth mentioning are under development in Brazil:

- The Brazilian Wood BIG-GT Demonstration Project WBP/SIGAME, based on the TPS technology, using a circulating fluidized bed reactor integrated to a gas turbine on a combined cycle (BIG/GT-CC). It is estimated that for this project, if wood chips are used as feedstock at a price of US$ 1.5/GJ, for an installed capacity of 32 MWe and an expected global thermodynamic efficiency of 37%, the capital unit cost would be around US$ 2500/kWe.

- Development of a BIG-GT system based on the TPS technology applied to a sugarcane/ethanol mill. In Brazil, this project is being developed by COPERSUCAR.
-

Table 15.12.6 Most important BIG-GT demonstration projects

Project and Location	Gasification Process	Gasification Technology	Biomass	Power Cycle
Burlington, VT, EUA	Indirect heating, low pressure and steam injection	FERCO/ Batelle	Wood	Gas turbine
PICHTR-Pacific International Center for High Technology Research, Hawaii, EUA	Direct heating, air or oxygen injection, pressurized bubbling fluidized bed-PBFB	IGT/Renugas	Sugarcane bagasse	Gas turbine
WBP-Brazilian Demonstration Project, Mucuri, BA, Brasil	Direct heating, air injection atmospheric circulating fluidized bed-ACFB	TPS	Wood chips (eucalyptus)	Combined cycle based on GE LM 2500
ARBRE Energy (arable biomass renewable energy), Yorkshire, UK	Direct heating, air injection, atmospheric circulating fluidized bed-ACFB	TPS	Short rotation coppice (willow and poplar) and forestry waste	Combined cycle based on EGT Typhoon
Energy Farm, Bioelletrica S.p.A. Cascina, Italy	Direct heating, air injection, atmospheric circulating fluidized bed-ACFB	LURGI	Wood chips (poplar, robinia) and agricultural waste	Combined cycle based on Nuovo Pignone PGT10B
Biocycle, Finland	Direct heating, air injection, pressurized fluidized bed-PFB	U-GAS Renugas		District heating based on EGT Typhoon
MVAP "Alfalfagas", Granite Falls, Minessota, EUA	Direct heating, air injection, pressurized fluidized bed-PFB	Kvaerner/ Carbona based on IGT Renugas	Stems of Alfalfa	Combined cycle based on Westinghouse gas turbine
Sydkraft AB, Värnamo, Sweden	Direct heating, air injection, pressurized fluidized bed-PFB	Bioflow/ Foster Wheeler Energy International	Wood residues and chips	Combined cycle/District heating based on EGT

5.12.6. (continued)

Project and Location	Plant Capacity	Estimated efficiency (%) (HHV)	Tar removal Process	Final Gas Cleaning System	Investment Cost (1st plant)	Proposal and Status
Burlington, VT, EUA	12-15 MWe 42 MW (gasifier)	30-35	Catalytic, dolomite	Cyclone and water quench		Commercial, co-firing now, GT after
PICHTR-Pacific International Center for High Technology Research, Hawaii, EUA	3-5 MWe, 10 ton/day	30-35	NA	Ceramic filters		Pilot plant, gasifier test (the plant is not operating, was dismantled)
WBP-Brazilian Demonstration Project, Mucuri, BA, Brasil	32 MWe	37	Catalytic, dolomite	Filter and wet Scrubbing	US$ 2500/kWe (1998)	Cancelled in 2003
ARBRE Energy (arable biomass renewable energy), Yorkshire, UK	8 MWe	31	Catalytic, dolomite	Fabric filter and water Scrubbing	2100 ECU/kWe (1998)	Demo, In construction
Energy Farm, Bioelletrica S.p.A. Cascina, Italy	12.1 MWe	32	NA	Fabric filter and water Scrubbing	2650 ECU/kWe (1998)	Demo, Planned to 2000, Interrupted project.
Biocycle, Finland	7.2 MWe 6.8 MWth	40 (electricity) 77 (cogeneration)	NA	Ceramic Filters	4750 ECU/kWe (1998)	Interrupted project
MVAP "Alfafagas", Granite Falls, Minessota, EUA	75 MWe	40	NA	Ceramic Filters		Commercial, Interrupted project.
Sydkraft AB, Värnamo, Sweden	6 MWe 9 MWth	32 (electricity) 83 (cogeneration)	Thermal Cracking	Ceramic Filters	5350 ECU/kWe (1998)	Demo, Commissioned 1996, Presently deactivated

IA: Information not available; FERCO - Future Energy Resources Corporation; MVAP Minnesota Valley Alfafa Producers
Iigh-energy costs and lack of interest for commercial application lead to several "stand still" situations.
ource: Walter et al. In Rosillo-Calle et al., 2000

Table 5.12.7. Main results of studies dealing with potential cost levels and performance of BIG/GT-CC system

Source	US$/kW$_e$	Efficiency (LHV) (%)	Capacity (MW$_e$)	Remarks
Eliott and Booth, 1993	1,300	nd	30	Projection for 10[th] plant
DOE (1998)	1,100 2,100	53 44	110 75	Outlook for 2030 (*turn-key*) Base case
Williams & Larson, 1996	1,000 1,200	51 44	97 39	Concepts considered include ISTIG (*turn-key*)
TPS (1997)	2,700 1,400 (turn-key)	 42-52 56-58	30 55 21-122 >100	Base level 1[st] plant Obtainable after the "Nth plant" Outlook for 2005 Outlook for 2020
Faaij, A. et al., 1998	4,000 2,000 1,600 1,100	39 54 55 59	29 51 110 215	Base case; full project cost Advanced cases, Outlook for 2015 for full project cases

Source: Walter et al. In Rosillo-Calle et al., 2000

AIII-5. 13 Charcoal production from biomass – World

AIII-5.13.1 Introduction

Charcoal is a major economic activity in many developing countries, particularly in Brazil, Africa, and Thailand, which is expected to increase significantly in the future e.g. from about 157 million bOE in 1995, 294 million bOE in 2010 and about 406 million bOE in 2020[31]. This could have serious socio-economic and environmental implications.

In Brazil, industrial charcoal has been produced for four centuries although it did not reach maturity until the 1960s. Charcoal production peaked in 1989 with a total production of 45 million m^3 compared to 25.5 million m^3 in 2000. Historically the bulk of charcoal has been produced from native forests but for the past two decades there has been a gradual phasing out in favor of plantations e.g. in 1990 about 66% of the charcoal originated from native forests, compared to about 28% in 2000, while the rest came from plantations, 34% and 72%, respectively.

Following is a brief description of industrial production of charcoal in Brazil, with emphasis on charcoal-making technologies and its wider socio-economic and environmental implications

AIII-5.13.2 General background

Charcoal in produced in large quantities, but it is extremely difficult to estimate global charcoal production since in most cases it is an integral part of the informal economy of many developing countries, characterized by small scale operations involving a very large number of small farmers, and rural poor people. Estimates vary widely, ranging from 26 to over 100 million ton (104 to 400 M m^3) of charcoal produced annually worldwide (Rosillo-Calle et al. 1996 & Rosillo-Calle & Bezzon 2000). But this is certainly a conservative estimate; what is clear is that demand for charcoal will continue to grow, particularly in Africa and in some countries of Southeast Asia, as urban dwellers and many small-scale industries, shift increasingly to charcoal and other more convenient sources of energy.

Estimated charcoal production and forecasts for developing countries, from 1995 to 2020, are summarized in Table 5.13.2 based on data prepared by the IEA. These estimates are, roughly, 161, 294, and 406 million bOE for 1995, 2010, and 2020 respectively. In 1995 Asia was the largest producer with 9.1 million toe, followed by Africa with 47 million bOE and Latin America with 45 million bOE. The main feature is that the IEA foresees an almost threefold increase in charcoal production and use,

31 The wood equivalent is approx. 490, 959, and 1,344 million bOE (barrel of oil equivalent), taking into account energy losses during the process of charcoal production. One bOE corresponds, approx. to 0.414 ton of wood, but this can vary.

which in fact could easily be an underestimate. This expected increase runs contrary to the general view.

Various aspects are worth emphasizing with regard traditional charcoal production, including:

The enormous socio-economic importance of charcoal production and use in developing countries e.g. hundred of thousands, even million, of people depend totally or partially on this activity. An estimated 200 to 300 million people use charcoal as their main source of energy around the world;

The low energy efficiency and technology base (e.g. 12% in Zambia, 11 to 19% in Tanzania, 9 to 12% in Kenya) results in considerable waste of resources as well as in serious environmental impacts;

Contrary to general belief, charcoal production is not the main cause of deforestation in the majority of the cases as has often been portrayed. There are of course many negative activities caused mainly by charcoal producers, rooted in socio-economic and cultural practices;

The environmental implications associated with charcoal production can be serious. Recent data indicate that emissions are much higher than previously thought[32];

A major preoccupation in charcoal production is the slow pace of technological development. Indeed this technology has remained, in the main, unchanged for centuries except for a few exceptions. One of the reasons is that charcoal is mostly an activity of the poor who are struggling to survive, let alone invest in technological improvements. Only a few countries that use charcoal for industrial purposes, such as Brazil, have put some resources into R&D, but even in these cases in a very limited scale. Charcoal is an activity that suffers considerably from low prestige and scientists and technologists prefer other alternatives. Thus, charcoal is an activity manned mainly by a semi-skilled and unskilled labor force.

Low technological development has become a serious problem. This needs to be overcome if the industry is to increase its efficiency and improve its environmental image, so badly needed at all levels[33]. This will be a long and arduous process since this is hardly a research priority except in some specific industries.

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32 New studies in the past few years are indicating that the effects of charcoal production are much higher than predicted e.g. approx. 0.65-1.41 kg CO_2 equivalent per kg of charcoal produced (for further information: www.ecoharmony.com) which makes charcoal one of the most GHG intensive activities. However, this is due to a combination of factors one of which is the extreme inefficiency of charcoal production methods in many of the poorest countries, poor housing, cultural practices, etc.

33 The main areas that need immediate attention are sustainable energy forest, harvesting, handling, transport, charcoal end uses, ash disposal, etc.

Table 5.13.2 Estimated and forecasted charcoal production in developing countries for the years 1995, 2010, and 2020

Region	1995	2010	2020
East Asia			
- Share of charcoal in final biomass use	5%	7%	8%
- Charcoal production/use (million bOE)	39	54	64
- Wood input in charcoal production (million bOE)	115	152	176
- Energy losses in charcoal transformation (million boe)	76	98	111
South Asia			
-Share of charcoal in final biomass use	2%	3%	4%
-Charcoal production/use (million bOE)	24	55	78
-Wood input in charcoal production (million bOE)	88	197	276
- Energy losses in charcoal transformation (million bOE)	64	142	199
Latin America			
- Share of charcoal in final biomass use	9%	9%	9%
- Charcoal production/use (million bOE)	45	49	50
-Wood input in charcoal production (million bOE)	92	101	104
- Energy losses in charcoal transformation (million bOE)	48	52	54
Africa			
- Share of charcoal in final biomass use	3%	6%	8%
- Charcoal production/use (million bOE)	48	134	216
-Wood input in charcoal production (million bOE)	189	505	785
- Energy losses in charcoal transformation (million bOE)	142	371	569
Total developing countries			
- Share of charcoal in final biomass use	3%	4%	5%
- Charcoal production/use (million bOE)	156	293	408
-Wood input in charcoal production (million bOE)	485	955	1341
- Energy losses in charcoal transformation (million bOE)	329	663	933

Source: IEA (1998) and ABRACAVE (2002)

Charcoal has played a key role in many industrial activities e.g. it was the predominant fuel in the iron industry before the Industrial Revolution. In England, for example, large trails of land were deforested causing devastation of forests in many parts of the country; by the mid 16th century the deforestation situation became so bad in some areas that a series of enactments intended to preserve the country's woods were issued (Schubert, 1957).

During the first few decades of the 20th century the growing demand for steel in many countries, together with the growing capacity of the chemical industry, brought about an unprecedented demand for charcoal and its liquid by-products.

However, when refined bituminous coal, coke and lignite became competitive with charcoal, the decline of the charcoal industry began once again. The development of `rapid pyrolysis' in late 1950s, opened up a new category of raw materials such as industrial wastes and agricultural and forestry residues, which were until then untapped (Rosillo-Calle et.al, 1996 & 2000).

In recent years, the availability of coke, together with supply difficulties of charcoal, cast a shadow on the long term future of the steel-based charcoal industry except for specialty steel products.

AII-5.13.3 Brazil

Traditional charcoal production is primarily from forestry residues resulting from the expansion of agriculture and pastures land, waste from wood processing, sawmills, forestry's thinning, and more professionally, from dedicated plantations. There are three major differences in Brazil with regard to other developing countries:
Brazil is the more efficient producer of large-scale industrial charcoal, with efficiencies ranging between 30-35%, particularly from plantations;
Brazil is the world’s largest producer and consumer of industrial charcoal;
Charcoal is increasingly becoming a professional activity with most charcoal being produced from dedicated plantations e.g. in 2000 about 72% of charcoal was produced from eucalyptus plantations, compared to 34% in 1990 (see Table 5.15.3).

Traditional charcoal production still represents a major economic activity (primary and secondary) for many rural laborers and small farmers in Brazil, particularly in areas where there is still a charcoal-making tradition such as Minas Gerais (MG). But this is a rapidly decreasing and is becoming marginalized activity e.g. in 1989 there were 267,500 employed in this industry compared to about 102,000 in 2000[34]. Charcoal production suffers from low prestige and unskilled labor, and this is having a negative effect on this industry.

The future of the charcoal industry is very much intertwined with steel, metallurgy, and cement industries. In addition, the charcoal industry will also be shaped by its ability to modernize, make better use of by-products, increasing professionalism, continuous utilization of plantations, and so forth.

34 For further information: www.silviminas.com.br/MOESCV.HTM

Table 5.13.3. Charcoal production in Brazil, 1990 – 2000 (Million m³)

Year	Charcoal from native forests	Percentage (%)	Charcoal from plantations	Percentage (%)	Total
1990	24.4	66.1	12.5	34.0	36.9
1991	17.9	57.7	13.1	42.3	31.0
1992	17.8	61.1	11.4	38.9	29.2
1993	17.9	56.5	13.8	43.5	31.7
1994	15.2	46.0	17.8	54.0	33.0
1995	14.9	48.0	16.2	52.0	31.1
1996	7.8	30.0	18.2	70.0	26.0
1997	5.8	25.0	17.8	75.0	23.6
1998	8.6	32.6	17.8	67.4	26.4
1999	8.1	30.0	18.8	70.0	26.9
2000	7.2	28.3	18.2	71.7	25.4

Source: ABRACAVE (2002).

The expansion of the agricultural and pasture lands have had a very serious effect on deforestation in the Brazilian Southeast region, of which charcoal production has also played a role, particularly in the state of MG where deforestation now represents about 80% of the total area. However, deforestation has been a misunderstood issue, often associated with large-scale charcoal production from native forests, a simple explanation to a very complex issue. Growing environmental concerns have resulted in the introduction of new environmental regulations since early 1990s, which is having a direct effect in the production of charcoal from native forests, particularly in the state of MG. New laws require progressive reduction on the use of native forests for charcoal production so that the pig-iron and steel industry becomes self-sufficient in charcoal, either from plantations or from sustainable forestry management projects.

Environmental pressures are forcing a rethinking of the charcoal-based industrial sector with significant implications for this industry future direction. For example, some steel companies are replacing charcoal for coke while others, like Mannesmann and many small independent pig iron producers, are concentrating efforts to cut costs by:

- increasing the overall efficiency, and
- by concentrating charcoal production from eucalyptus plantations with the aim of achieving self-sufficiency. This will have the additional benefit of reducing transportation costs significantly as most of these plantations will be located near the consuming centers.

However, this is not generally happening. While charcoal from plantations is increasing rapidly, new plantations are not being planted at the same rate e.g. the annual plantation requirement to supply all charcoal demand is estimated at 80,000 ha/yr, compared with a current reforestation rate of 37,000 ha/yr. This is causing serious supply problems and forcing the industry to fetch charcoal as far away as in the states of Mato Grosso do Sul, Bahia and Goias, with serious implications for the long-term future of the charcoal industry.

OTHER SOURCES AND USES OF BIOMASS

AIII-5. 14 Biomass direct combustión

AIII-5.14.1 Introduction

Combustion technologies play a major role throughout the world, producing about 90% of the energy from biomass. Combustion technologies convert biomass fuels into several forms of useful energy e.g. hot air, hot water, steam, and electricity. Commercial and industrial combustion plants can burn many types of biomass ranging from woody biomass to MSW.

The simplest combustion technology is a furnace that burns biomass in a combustion chamber. The hot gases released as biomass fuel contains about 85% of the fuel's potential energy. A biomass-fired boiler is a more adaptable technology that converts biomass to electricity, mechanical energy, or heat. A boiler transfers the heat of combustion into steam. The steam output contains 60 to 85% of the potential energy of the fuel. Biomass combustion facilities that generate electricity from steam-driven turbine generators have a conversion efficiency of 17 to 25%. Cogeneration can increase this efficiency to almost 85%. The large-scale combustion systems use mostly low-quality fuels, while high-quality fuels are more frequently used in small application systems.

The selection and design of any biomass combustion system is primarily determined by the characteristic of the fuel to be used, environmental constrains, cost of equipment, size of plants, etc. Emissions reduction and efficiency are major goals (for further information: www.ieabioenergy-task32.com/handbook.html).

Combustion technology still needs to be optimized. In particular, there is a need to meet demand for lower costs, increased fuel flexibility, lower emissions, increased efficiency, flue gas cleaning, particulate formation, multi-component and multi-phase systems, NOx and SOx formation, maximize safety and simplify operations. This is particularly more pressing if competitiveness with gasification and pyrolysis is to be maintained as these technologies are actively being promoted.

Interest in wood-burning appliances is increasing; these range from heating, cooking, to interior decoration. Domestic wood-burning appliances include fireplaces, heat storing stoves, pellet stoves and burners, central heating furnaces and boilers, etc, particularly European rather than an worldwide trend.

There are various industrial combustion systems available, which broadly speaking can be defined as fixed-bed combustion (FxBC), fluidized bed combustion (FBC) and dust combustions (DC) (Table 5.14.1).

Table 5.14.1. Large-scale combustion systems

System	Remarks
Fixed bed combustion (FxBC) systems include grate furnaces, and underfeed stokes	Grate furnaces are better for burning biomass fuels with high moisture content, different particle sizes, and high ash content. Usual capacity goes up to 20 MWth (in Brazil capacity is over 1000 MWth). Underfeed stokes represents a cheap safe technology for small and medium scale systems, up to 6 MWth.
Fluidized bed (FBC). Depending on the fluidization velocity, they can be categorized as bubbling (BFBB) and circulating fluidized bed combustion CFBC)	Biomass fuels are burned in a self-mixing suspension of gas and solid bed material in which air for combustion enters from below. FBC plants are better suited for large-scale applications, 30 + MWth. For smaller plants FxBC are usually more cost-effective.
Dust combustion (DC). In DC, a mixture of fuel and primary combustion air is injected into the combustion chamber.	DC is suitable for biomass fuels available in small dry particles such wood dust. Fuel feeding needs particular control due to the explosion-like gasification process of the biomass.

Source: Compiled from: IEA, 2004.

AIII-5.16.1 AIII-5.14.2 Electricity generation from biomass

According to ANEEL, in 2001 the country had approximately 1,330 power plants in operation generating around 87 GW. As indicated in Table 5.14.2 biomass facilities were responsible for 3.16% of the domestic installed capacity.

Table 5.14.2 Biomass Power Plants in Brazil			
Fuel	Quantities	Power (kW)	%
Black Liquor	11	649,230	23.58
Rice straw	2	6,400	0.23
Sugarcane bagasse	191	1,953,927	70.96
Wood residues: sawdust, shavings, trim, bark, etc.	17	116,002	4.21
Biogas	2	20,030	0.73
Charcoal	1	8,000	0.29
Total	224	2,753,589	100
Source: MME (2003)			

As indicated in Table 5.14.2 sugarcane residues and black liquor are the most important biomass sources (by-products of the sugar/alcohol and pulp/paper industries).

A recently approved Federal Law[35] introduces significant improvements for the existing PROINFA, a Federal program providing incentives for the generation of renewable energy. This Law regulates approximately 3.3 GW of renewable energy sources (e.g. biomass, wind and small hydroelectric plants, directing 1.1 GW for each category).

According to the *Sociedade Brasileira de Silviculure* (SBS), wood consumption was approximately 300 x 10^6 m^3/yr million m^3 – (300 M m^3) better (natural and planted forest for all uses) during 2001. Approximately 100 x 10^6 m^3/yr were from planted forests cultivated for industrial applications. Total industrial consumption was approximately 166 x 10^6 m^3/yr. From this total, 32 x 10^6 m^3/yr were for the pulp/paper industry; 45 x 10^6 m^3/yr for charcoal; 29 x 10^6 m^3/yr firewood for industrial applications; and 60 x 10^6 m^3/yr for solid products (construction and furniture industries).

AIII-5.16.2 AIII-5.14.3 Dendroenergetic natural resources

As trees require time to grow and cannot be considered as an inexhaustible source of energy, they need to be adequately managed so that they continue to be available for human needs. However, ever-increasing cattle raising activities in developing countries are severely affecting important forest resources.

Extractive activities lead to catastrophic and irreversible consequences. However, studies show that well-planned practices can allow communities to extract energy resources from forests in a sustainable way.

35 Law No.10, 762 of November 11, 2003.

In Brazil, during the last decade, the rate of natural forest cutting has decreased sensibly, as described in Chapter 5.13.3 Table 5.14.3 indicates biomass productivity for sustainable activities within natural forests in Brazil (NOGUEIRA, et. al., 2000)[36], based on a density of 400 kg/m³ and a Low Heating Value (LHV) of 13.8 MJ/kg.

Table 5.14.3 Sustainable Productivity of Biomass of Natural Forests

Forest Covering	**Description**	**Productivity**	
		(m³/ha.yr)	**(bOE/ha.yr)**
Dense Tropical Forest	> 60% canopy	13.7	12.5
Open Forest	10 to 60% canopy	7.1	6.4
Woodsy (*Cerrado*, Bras.)	< 10% canopy	1.6	1.5

Source: Nogueira, et. al., 2000.

AIII-5.14.4 Biomass direct combustion

This includes stoker-fired combustion systems (e.g. static grates, dumping grates, chain graters, etc), cement kilns, FBC [i.e. atmospheric FBC, bubbling fluidized bed boilers (BFBB), circulating FBC, pressurized FBC, cyclone furnaces, and pulverized fuel boilers (PFB)]. The AFBC systems fired on mixtures of coal and wastes have been used for years and this technology is adopted in many countries for co-firing applications. The BFBB are tolerant to a variety of different fuel sources; CFBC is a commercially proven technology, with about 300 units operating around the world, and because it is fuel flexible, it allows the use of various fuels with different properties. The PFBC is a more recent advanced clean coal technology, and its use in cofiring is still at early stages of development. Commercial scale tests have been carried out using straw, miscanthus, wood and sewage co-fired with coal. Cyclone furnaces (a form of slugging combustor used primarily in utility boilers) are also well suited for cofiring with little modifications.

Most biomass used for energy generation in the world is used for direct combustion, with varying efficiency according to their different applications.

Direct combustion has always played an important role in Brazil. The average consumption of firewood in Brazil for the past 32 years was approximately 5.3 x 10^6 ton/yr, varying from 6.6 x 10^6 ton in 1988 to 4.7 x 10^6 ton, in 2002. Direct combustion for industrial and commercial applications is mostly done in steam boilers (140 x 10^6 bOE) (MME, 2003).

Figure 5.14.4 illustrates the behaviour of primary energy uses from forestry activities from 1940. Initially dominated by firewood, the Brazilian energy model has changed

36 This considers a density of 400 kg/m³ and a LHV of 13.8 MJ/kg

drastically through time. In 2002, available renewable energy sources (hydro and biomass) were greater than fossil fuels.

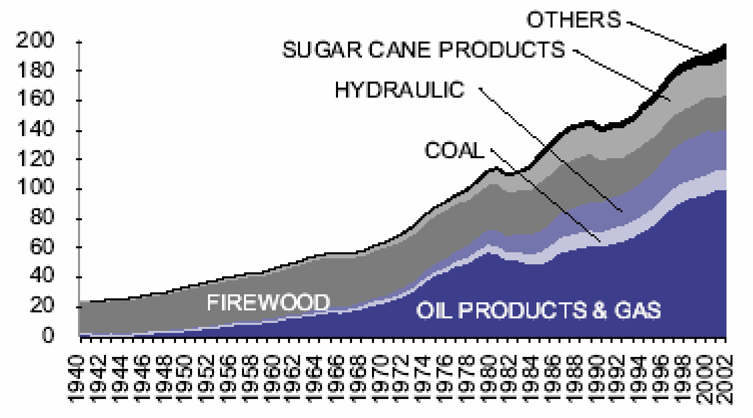

Figure 5.14.4 . *Gross Domestic Supply of Primary Energy Sources (Source: MME, 2003)*

Firewood use in Brazil is still significant, mainly in the charcoal industry and for household cooking and small-scale industries. Residential use of firewood was approximately 25 million tons in 2002, which corresponds to 33% of the national production (11.9% higher than 2001).

About 29 million tons (about 38% of domestic production) was used in the charcoal industry. The remaining 29% represents agricultural and industrial applications. In 2002, charcoal consumption increased by 4.5%, mainly directed to the iron and steel industries.

Various studies have indicated the economic feasibility of eucalyptus energy plantations cost for the development of "Energy Forests" vary between US$ 6-7/bOE under the current scenario.

AIII-5. 15 Agricultural waste for energy production

AIII-5.15.1 Introduction

Several types of agricultural residues can be used as fuels. Their energetic potential is not always known; even so, its use should be considered as an opportune and viable solution for its final disposition, reducing its volume and polluting potential.

Agricultural residues are constituted of straw, leaves, and stems and they have an average higher heating value of 15.7 MJ/kg of dry matter. Table 5.15.1a summarises estimated availability of vegetable residues from main commercial crops in Brazil.

Table 5.15.1a. Estimated Availability of agricultural crop Residues

PRODUCT	WASTE (t/ha)	DRY MATERIAL (%)
Rice	4.0 – 6.0	89.0
Sugarcane*	7.0 – 13.0	23.4**
Bean	1.0 – 1.2	89.0
Corn	5.0 – 8.0	90.5
Cassava	6.0 – 10.0	90.4
Soybean	3.0 – 4.0	88.5
Wheat	4.5 – 6.5	92.5

* dry base – waste only, not including bagasse (potential)
** approx. 80% burned in the pre-harvest
Source: Nogueira et. al., 2000

Perennial crops e.g. as coffee and orange, produce 2.5 kg of woody residues a year for each plant. Animal manure (cattle, swine, equine and birds) can be burned, and have an average lower heating value of 14.6 MJ/kg. However, the best way to obtain energy from it is through anaerobic fermentation, which produces biogas. Besides producing biogas, this process allows the production of organic fertilizer.

Table 5.15.1b presents some basic indexes for the evaluation of the energy potential from animal manure.

Table 5.15.1b. Estimated Availability of Animal Waste			
ANIMAL	**GENERATION OF MANURE* (kg/animal.day)**	**GENERATION OF BIOMASS (m^3/animal.day)**	**GENERATION OF ENERGY (bOE/animal.yr)**
Bovine	10.0	0.360	0.473
Equine	10.0	0.360	0.473
Buffalo	15.0	0.550	0.747
Swine (50 kg)	2.5	0.180	0.234
Bird (2,5 kg)	0.2	0.011	0.014

*Wet base manure

Source: Nogueira, et. al., 2000

Most of the agro-industry, including the sugar, ethanol, soluble coffee, wood, paper and cellulose sectors, as well as the slaughterhouses, produce residues in large scale and of high-energy value that can contribute to the reduction of external energy bought for the generation of vapor and/or electricity.

The energy from residues is obtained, in most cases, by directly burning in ovens and boilers, or through bio-fermentation. What determines the energy conversion process is its moisture contents because it is only practical to burn residues with not more than 50% humidity. Therefore, residues as the vinasse (from the production of ethanol), the effluents of slaughterhouses, milk processing facilities, etc, are more appropriate for biogas production. Table 5.15.1c below summarizes the potentials of production of three main residues.

Table 5.15.1c. Estimated Potential Production of Residues			
RESIDUES	PRODUCTION	High Heating Value (MJ/kg) dry basis	Availability
Sugarcane residues	250 – 300 kg/ton of cane	18.4	100 %*
Black Liquor	2.5 to 2.8 ton/ton of cellulose	12.5	80%
Coffee residues	4.5 ton/ton of soluble coffee	14.6	60 a 80%

* 80% 0f 50% (potential source)

Source: NOGUEIRA, et. al., 2000

The residues from the wood industry, like small branches and stems left in the field, represent 33% of the wood cut for industrial uses and 5% of the woodcut to burn. Therefore, there is a considerable for energy production, which would be even greater if the residues of the sawing operations were considered. In all these cases, the low heat value of the wood (13.8 MJ/kg) should be assumed.

AIII-5. 16 References

ABRACAVE – BRAZILIAN ASSOCIATION OF RENEWABLE FORESTS, 2002. Available at: www.abracave.com/br/anuario/ctCV.htm.

ALFRED SZWARC, 2002. Brazilian Association of Automotive Engineering presentation.

ANEEL - BRAZILIAN ELECTRICITY REGULATORY AGENCY, 2003. Available at: www.aneel.gov.br.

ANFAVEA, 2003. Statistical Yearbook of the Brazilian Automotive Industry – 2003. Associação Nacional dos fabricantes de Veículos Automotores – ANFAVEA.

AZAR, C., LARSON, E., 2000. Bioenergy and land-use competition in Northeast Brazil, Energy for Sustainable Development, Volume IV No. 3, October 2000, Department of Physical Resource Theory, Chalmers University of Technology/Göteborg University, 412 96 Göteborg, Sweden, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ 08544, USA.

BLACKADDER, W., LUNDBERG, H., RENSFELT, E. AND WALDHEIM, L. Heat and Power Production Via Gasification in the Range 5-50 Mwe. Advances in Thermochemical Biomass Conversion, Intelaken, Switzerland, May 11-15, 1992, 27p. In: Olivares-Gómez E. Resultados Preliminares da Gaseificação de Bagaço-de-Cana em Reator de Leito Fluidizado Borbulhante. Dissertação de Mestrado, Universidade Estadual de Campinas-UNICAMP, Campinas, São Paulo, 1996.

BLUE TOWER, 2004. Tecnologia EM 1-2 Blue Tower. Available in http://www.edrb.com.br.

BRACELPA - ASSOCIAÇÃO BRASILEIRA DE CELULOSE E PAPEL; Números do Setor 2001; www.bracelpa.org.br.

Brazil/U.S. Aspen Global Fórum, 2000. Task Forces on Early Start Projects for Carbon Emission Reduction, São Paulo, Brazil, June 22-24.

CGEE, 2003. MACEDO, I.C. e JANNUZZI, G.M. Estado da Arte e Tendências das Tecnologias para Energia, Centro de Gestão e Estudos Estratégicos-CGEE.Technical Report CTEnerg, Janeiro, 76p., available in http://www.cgee.com.br (in Portuguese).

COPERSUCAR, 2004. Private communication with Copersucar experts.

COUTO, L. ET AL., 2002. “Florestas plantadas para energia: sustentabilidade e economia”, na conf. “Sustentabilidade na geração e uso de energia no Brasil: os próximos vinte anos”, Acad. Bras. De Ciências / UNICAMP.

CTNERG, 2003. “Estado da arte e tendências tecnológicas para energia” CGEE.

CZERNIK, S. AND BRIDGWATER, A.V., 2004. Overview of Applications of Biomass Fast Pyrolysis Oil. Energy & Fuels, 18, 590-598.

GOLDENBERG, J., 2004. Private communication.

DA SILVA, W.A.C. e HORTA-NOGUEIRA, L.A., 1997. Produção de Eletricidade a partir da Biomassa. In: Cortez, L.A.B. e Silva. E.L.Tecnologias de Conversão Energética da Biomassa-Série Sistemas energéticosII. 1ª edição, Manaus-EDUA/EFEI, Brasil, editora da Universidade de Manaus/EFEI, volume único, 540 p., p. 463-507.

DAI – DOWNSTREAM ALTERNATIVES INC., 1997. Drivability and Performance of Reformulated and Oxygenated Gasoline. DAI information Document #970302, March.

DEEPCHAND, K., 2003. Bagasse Energy Cogeneration in Mauritius. Available at: www.afrepren.org/Pubs/WorkingPapers/wpp246_sum.htm.

EMBRAPA - Embrapa Mandioca e Fruticultura, 2003. Available at: www.cnpmf.embrapa.br.

EMBRAPA, 2004. Private communication with EMBRAPA experts.

FAAIJ, P.C.A., HAMELINCK, N.C., LARSON, D.E. AND KREUTZ, G.T., 1999. Production of Methanol and Hydrogen from Biomass via Advanced Concepts-Preliminary Results. Proceedings of the Fourth Biomass Conference of the Americas-Biomass: A Growth Opportunity in Green Energy and Value-Added Products, Addendum, August 29 to September 02.

FAIR, 2004. *FAIR-CT96-1913.* SORGHUM: Environmental studies on sweet and fiber sorghum sustainable crops for biomass and energy. Available at: www.nf-2000.org/secure/Fair/S664.htm.

FAO - FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2003. Available at: www.fao.org.

FAO - FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2004. Available at: www.fao.org.

FERRES, J.D., 2002. "Bio-diesel", no seminário "Os veículos automotores e o efeito estufa", ABIOVE; AEA, São Paulo, Março.

FUELS FOUNDATION, 1996. Changes in Gasoline III – The auto technician's gasoline quality guide, 1996. Renewable Fuels Foundation.

GOLDEMBERG, J., 2004. Private communication.

GREGOIRE, C.E., 1992. Techno economic Analysis of the Production of Biocrude from Wood. National Renewable Energy Laboratory-NREL, report TP-430-5435, USA.

HERMAN & ASSOCIATES, 2003. Automobile Manufacturer Fuel Recommendations – Vehicle Owners Manual Statements.

IBAMA, 2004. Private communication with IBAMA experts.

IEA - INTERNATIONAL ENERGY AGENCY, 2004. Available at: www.ieabioenergy-task32.com/handbook.html.

IEA - INTERNATIONAL ENERGY AGENCY, 1998. IEA biomass energy analysis and projections, in: Biomass Energy: Data, Analysis and Trends, OECD/International Energy Agency, Paris, pp.151-166.

IPT-Technology Research Institute of State of São Paulo, 2003. Integrated Biomass Project-PIB. Final Report Nº 66 899-i/318, FINEP Accord Nº 77.98.0087.00, São Paulo, Brazil.

JOSEPH JR., H., 2004. Volkswagen do Brasil and ANFAVEA (private communication).

LARSON, E.D., WILLIAM, R.H. and LEAL, M.R.L.V., 2001. A Review of BIG/GT Technology and its Application in Sugarcane Industries, with an Analysis for Cuba. Energy for Sustainable Development, vol. V, Nº 1, March.

LEÃO, R.M., 2000. "A floresta e o Homem", IPEF, USP; Edusp.

MCT, 2002. Programa Brasileiro de Bio-Combustíveis – Probiodiesel, MCT-SPTE, Abril.

MMA - MINISTÉRIO DO MEIO AMBIENTE, 2002. Critérios de Elegibilidade e Indicadores de Sustentabilidade para Avaliação de Projetos que Contribuam para a Mitigação das Mudanças Climáticas e para a Promoção do Desenvolvimento Sustentável [internal publication].

MME – MINISTÉRIO DE MINAS E ENERGIA, 2003. BEM – BALANÇO ENERGÉTICO NACIONAL; Brasília; Ministério de Minas e Energia, 45p.

MUTANEN, K., 1993. Opportunities for Bioenergy in Power Generation. In: Electric Utility Congress, June 15 and 16th, Boston.

NIGRO, F.E.B., 2004. Institute for Technological Research (IPT) (private communication).

NOGUEIRA, L. A. H., ET. AL., 2000. "Dendroenergia: fundamentos e aplicações". Brasília: ANEEL.

NOGUEIRA, L.H., 2004. "Biodiesel: como e porque", apresentação no Fórum Permanente de Energia & Ambiente, Universalização do Atendimento de Energia Elétrica e Geração Distribuída, Abril.

OLIVARES-GÓMEZ E. 1996. Resultados Preliminares da Gaseificação de Bagaço-de-Cana em Reator de Leito Fluidizado Borbulhante. Dissertação de Mestrado, Universidade Estadual de Campinas-UNICAMP, Campinas.

OLIVARES-GÓMEZ E., 2002. Estudo da Pirólise Rápida de Capim Elefante em Leito Fluidizado Borbulhante mediante a Caracterização dos Finos de Carvão. PhD.Thesis, FEAGRI, Universidade Estadual de Campinas-UNICAMP, Campinas.

OLIVEIRA, L.B. 2001. "Biodiesel – Combustível limpo para o transporte sustentável" *in* RIBEIRO, S.K. (coord.). "Transporte Sutentável: alternativas para ônibus urbanos" COPPE/UFRJ.

PAGLIARDI, O.; MESA-PÉREZ, J.M.; ROCHA, J.D.; OLIVARES-GÓMEZ, E.; CORTEZ, L.A.B., 2004. Aspectos da Viabilidade Econômica de uma Planta de Pirólise Rápida de Biomassa. Anais do IV Congresso Brasileiro de Planejamento Energético (material em edição), Universidade Federal de Itajubá-UNIFEI, Itajubá, MG, Brazil (in portuguesse).

PIRNIE, M. - Malcolm Pirnie, Inc, 1999. The Road to Fuel Cell Vehicles: A National Forum. Available at: www.methanol.org.

PYNE- Pyrolysis Network, 2004. Avalilable at: www.pyne.co.uk.

RAAD, T., V&MT do Brazil. Private Communication. In: tulraad@vmtubes.com.br. Access by www.vmtubes.com.br.

ROSE, L.P. *et al;* 2002. "Óleos vegetais" – Workshop
"Análise Prospectiva de Introdução de Tecnologias Alternativas de Energia no Brasil", COPPE.

ROSILLO-CALLE F., BAJAY S. V., & ROTHMAN H. Eds., 2000. Industrial Uses of Biomass Energy- Taylor & Francis, London, pp 183-199.

ROSILLO-CALLE, F. DE REZENDE M A A., FURTADO, P., AND HALL, D.O., 1996. The Charcoal Dilemma- Finding s Sustainable Solution for Brazilian Industry, IT Press, London.

SBS - SOCIEDADE BRASILEIRA DE SILVICULTURA. 2002. Estatísticas 2001; www.sbs.org.br.

SCHUBERT H. R., 1957. History of the British Iron and Steel Industry, Rantledge & Keagan Paul, London.

SILVA, T. I., *et. al.*, 2002. "Geração de Energia a Partir de Resíduos de Mandioca para Agricultura Familiar no Estado do Pará". In: Anais do 4°. Encontro de Energia no Meio Rural. Campinas, São Paulo.

SMA-Secretariat of the Environment, Government of the State of São Paulo, 2004. Assessment of Greenhouse Gas Emissions in the Production and Use of Fuel Ethanol in Brazil. By: MACEDO, I.C.; LEAL, M.R.L.V. and SILVA, J.E.A.R. Report, March.
SOTREQ, 2004. Private communication. Available at: www.sotrec.com.br.

TPS - TERMISKA PROCESSES AB., 2004. Gas Turbines and Reciprocating Engines. Available at: www.tps.se/gasification/gasturb_en.htm.

UFPR – Federal University of Parana State, 2004. Private communication with UFPR experts.

UNICA - Açúcar e Álcool do Brasil, 2004. Private communication with UNICA experts.

UNICA - Açúcar e Álcool do Brasil, 2004. Commodities da Energia e do Meio Ambiente, São Paulo, May.

US DEA – United States Department of Energy, 2000. Available at www.doe.gov.

US DOE - U.S. DEPARTMENT OF ENERGY, 2003. Renewable Energy Annual 2001 - U.S. Department of Energy, Energy Information Administration.

VERDE LEAL, M.R.L., 2004. Copersucar (private communication).

WALTER, A.C. DA SILVA; FAAIJ, A. AND BAUEN, A., 2000. New Technologies for Modern Biomass Energy Carries. In: Rosillo-Calle, F.; Bajay S. and Rothman, H. Industrial Uses of Biomass Energy: The example of Brazil. First Edition. London, England, published by Taylor & Francis, volume único, 2000, p. 200-253.

WALTER, A.C. DA SILVA; FAAIJ, A. AND BAUEN, A., 2000. New Technologies for Modern Biomass Energy Carries. In: Rosillo-Calle, F.; Bajay S. and Rothman, H. Industrial Uses of Biomass Energy: The example of Brazil. First Edition. London, England, published by Taylor & Francis, 2000, pp. 200-253.

V&MT - VALLOUREC & MANNESMANN TUBES, 2004. Raad, T., V&M Florestal. Private Communication. Private Communication.

WTE - INTERNATIONAL SOLID WASTES ASSOCIATION. Energy from Waste, State-of-the Art Report. Available at: www.wte.org.

SUMMARY OF IMPORTANT DATA
overview of Brazilian biomass distribution and use

LAND USE – BRAZIL		
CATEGORIES	TOTAL AREA KM^2	SOURCE (ESTIMATION MODEL)
Total Area (Brazil)	8,514,877	IBGE, 2004*
Native Forests [1]	5,500,000	EMBRAPA, 2003
Brazilian Native Amazon (primary forest)	3,700,000	EMBRAPA, 2003
Secondary Amazon and other native forests including Atlantic Forest, Rough Cerrado [2], etc.	1,800,000	EMBRAPA, 2003
Planted Forests		
Planted Forests (cellulose and energy) [3 4 5]	~ 60,000	SBS, 2003
Other Planted Forests [6]	~ 155,000**	SBS, 2004, IBAMA, 2004, UFPR, 2004
Pasture Land [7]	1,970,000	FAO, 2001
Agricultural Land		
Present Crop Land	700,000	FAO, 2001
Current Sugarcane Crop Land	53,000	COPERSUCAR, 2004
Land suitable for sugarcane [8]	~ 1,000,000	UNICA, 2004
Land suitable for crop land (ultimate potential) [9]	3,776,000	IBGE, 2003

* Primary Data Source.

** Information from experts.

[1] According to research institutes from Brazilian Universities (UFPR, ECO-UNICAMP, EMBRAPA, UFV), probably only 55% of native forests strictly include the Amazon Forest (Rain Forest). A significant portion of the remaining includes what is called "Heavy or Rough Cerrado" or "Cerradão", which is a transitory form of forest (between the Rain Forest and the Cerrado) formed mostly by dense forest areas. Some areas in the States of Mato Grosso, Tocantins, Rondonia, and Maranhão, also include areas of Cerradão within this same "Native Forest" category.

[2] Cerrado is a variety of savanna.

[3] Probably the most reliable data-source for planted Forests comes from the SBS (Sociedade Brasileira de Silvicultura) an organization represented by the Brazilian Forestry Sector, which includes the main companies involved in following sectors: rubber, iron mills, paper-pulp, electricity, etc. Although several models have been used to estimate current planted forests, crop and pasture lands, the only primary source (probably with the exception of some specific works from INPE) is IBGE. IBGE data is primarily based on reports provided by landowners. Because of strong economic, fiscal, and environmental interests, these sources are not fully reliable.

[4] RPPN – Reserva Particular do Patrimônio Natural, exotic and other commercial forests.
[5] Mostly rubber trees, pines, eucalyptus, araucaria, and acacia.
[6] Some research institutions include in this specific category some non-traditional trees, which have been increasingly occupying more areas for commercial purposes. These trees include coconut tree, palm-plant, Açaí, etc.
[7] Cattle-raising in Brazil is in great part done inefficiently. The ratio "cattle herd" / "pasture area" could be significantly optimized making large areas available for agricultural use. Growth of the Meat Industry has been wrongly attributed to the deforestation of primary Amazon forest. Meat Industry growth is mostly due to investments in efficiency and genetics, which includes significant reduction in levels of methane emissions.
[8] Including areas currently used for pasture and other crops – without significant environmental damage, mainly deforestation. Sustainable Rotation Practices (mosaic/zoning) could provide sustainable sugarcane practices. Crop Rotation would include sugarcane, soybean, and pastures.
[9] Available but not currently being used. This does not include areas that could be illegally deforested or lead to significant environmental impacts. Further optimization of cattle-raising may ultimately allow significant areas for crops. Public Policies may be the key facto to further increase productivity.

BIOMASS USED FOR THERMOELECTRIC GENERATION				
Feedstock (Biomass Source)	# of Facilities	Installed Capacity (MWe)	%	Source
Black Liquor	11	649	22.5	ANEEL, 2003
Rice Husk	03	14	0.5	ANEEL, 2003
Sugarcane Bagasse	318	~ 2,000	69.7	UNICA, 2004[1]
Wood Chips	18	160	5.6	ANEEL, 2003
Biogas	2	~ 40	1.4	ANEEL, 2003; SOTREQ, 2004 [1]
Charcoal	1	8	0.3	ANEEL, 2003
Total	343	~ 2871	100	

[1] Including information from the respective sectors, as informed by experts.

LIQUID FUELS				
Fuel Type (Biomass Source)	Area Used (ha)	% Currently produced as energy source	Productivity Crop Liquid Fuel	Source
Ethanol				
(Sugarcane)	5,300,000 [1]	~ 50%	83 ton / ha [2] 86 liters / ton [3]	COPERSUCAR, 2003 MACEDO, 2004; UNICA, 2003
(Cassava)	1,700,000	0%	22.6 tons / ha [4] 4,500 liters / ha [5]	MME, 1982 EMBRAPA, 2002 and CONAB, 2002
Biodiesel				
(Soy Bean)	21,100,000	0%	2.7 tons / ha 2,000 liters / ha [6]	ABIOVE and CONAB 2003 PARENTE, 2003

[1] Currently, the sugarcane sector includes approximately 60,000 producers and around 318 mills (85% in the Southeastern plus Mato Grosso and Mato Grosso do Sul, and around 15% from Northeastern states).

[2] Crop Productivity in Northeastern states is around 60 tons / ha, however, only 15% of sugarcane is produced in the region. Ethanol industrial productivity in Northeastern states is around 70 liters / ton. Only 15% of domestic sugarcane production comes from Northeastern states.

[3] Currently, approximately 50% of total sugarcane production is directed to the production of ethanol fuel (anhydrous and hydrous). The remaining 50% is directed to sugar processing. Production breakdown (Sugar / Hydrous Ethanol / Anhydrous Ethanol) will depend primarily on market prices.

[4] Southeastern Brazil and India reach productivities between 24 and 25 tons / ha.

[5] Ethanol productivity estimates considering total production area suggests values of 7,500 liters / ha.

[6] Soybean Oil.

PROCESS HEAT		
Type	Area Used (ha)	Production M^3
Charcoal		26.22
Native Forest		8.36
Planted Forest		17.85
Source: ROSILLO-CALLE, *et. al*, 2000.		

AIII-6 Wind Energy – Status and R&D Activities

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AIII-6.1 Different wind turbine types: an overview

Today there are various types of wind turbines in operation, (Figure 6.1 gives an overview). The most common device is the horizontal axis wind turbine. This turbine consists of only a few aerodynamically optimised rotor blades, which for the purpose of regulation usually can be tumbled about their long axis (Pitch-regulation). Another cheaper way to regulate it, consists in designing the blades in such a way that the air streaming along the blades will go into turbulence at a certain speed (Stall-Regulation). These turbines can deliver power ranging from 10 kW to some MW. The largest turbine on the European market has a power of 3.6 MW, bigger machines are testing. The efficiency of this type of turbine is very high. Therefore, it is solely used for electricity generation which needs "high speed engines" to keep the gear transmission and the generator small and cheap.

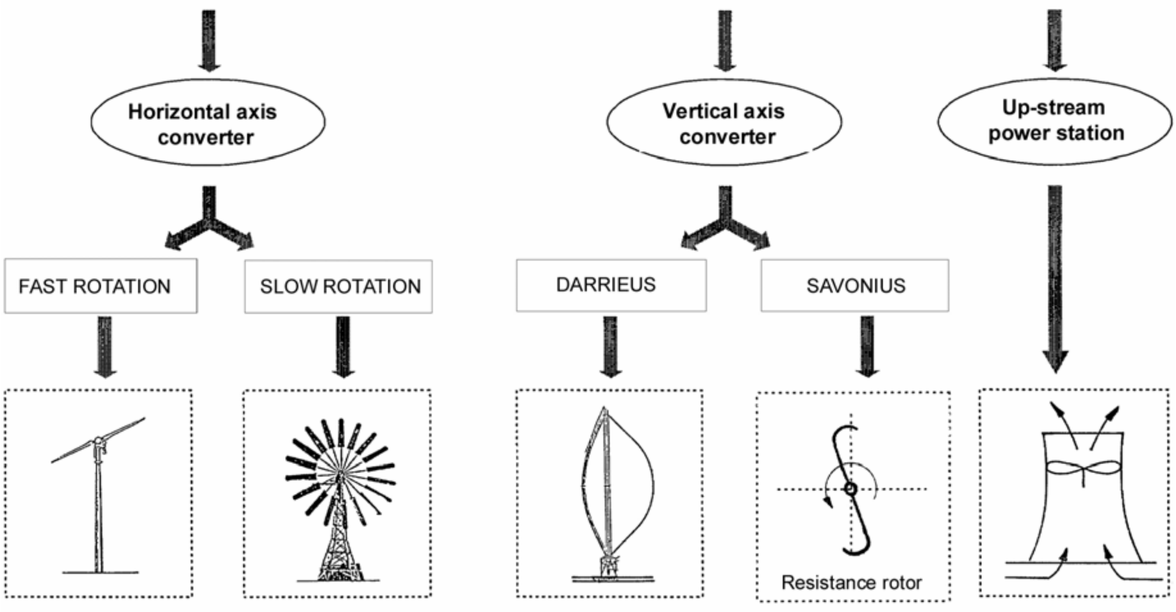


Figure 6.1: Overview of the different types of wind turbines

Another conventional (older) type of horizontal axis rotor, is the multi-blade wind turbine. It was first built about one hundred years ago. Such wind mills have a high starting torque which makes them suitable for driving mechanical water pumps. The number of rotations is low, and the blades are made from simple sheets with an easy geometry. For pumping water, a rotation regulating system is not necessary, but there is a mechanical safety system installed to protect the turbine against storm damage. By using a so called wind-sheet in lee direction the rotor is turned in the direction of the wind. In order to increase the number of rotations, this type of turbine had been equipped with aerodynamically more efficient blades facilitating the production of electricity, here the area of a blade is smaller.

The mechanical stability of such "slow speed turbines" is very high, some have had operation periods of more than fifty years.

A third type of turbine is known as DARRIEUS; a vertical axis construction. Their advantage is that they do not depend on the direction of the wind. To start, they need the help of a generator working as motor or the help of an SAVONIUS rotor installed on top of the vertical axis. In the nineteen eighties a reasonable number of DARRIEUS-turbines had been installed in California, but a further expansion into the higher power range and in the European markets has not taken place. One reason may be that they are noisier than horizontal axis turbines. Another disadvantage is that wind velocity increases significantly with height, making horizontal axis wheels on towers more economical. Nevertheless, there are some companies producing DARRIEUS-turbines in the very low power range of a few kilowatts for decentralised electricity supply in areas without electrical grids e.g. in rural areas of developing countries.

The Savonius rotor is only used for research activities, e.g. as a measurement device especially for wind velocity, it is not used for power production. Therefore it will not be discussed in detail in this paper.

The last technique to be dealt with is known as Up-Stream-Power-Station or thermal tower. In principle, it can be regarded as a mix between a wind turbine and a solar collector. In the top of a narrow, high tower is a wind wheel on a vertical axis driven by the rising warm air. A solar collector installed around the foot of the tower heats up the air. The design of the collector is simple; a transparent plastic foil is fixed over several metres on the ground in a circle around the tower. Therefore, the station needs a lot of space and the tower has to be very high. Such a system has a very poor efficiency, only about one percent. World wide there has only been one Up-Stream-Power- Station built so far, it was designed by a German company. For some years it worked satisfactorily at the location of Manzarenas in Spain, but in the mid eighties it was destroyed by bad weather. This station had an electrical power of 20 kW, the tower was about 200 m high, and the collector had a diameter of approximately the same size. A second Up-Stream-Power- Station with an electrical performance of 200 MW is now planned in Australia. The tower height is about 1000 m and the diameter of the collector area is about 7000 m. The project should be realised in 2008. The advantage of such a design is its technical simplicity, which may enable developing countries to construct it by themselves. But since there has been tremendous technical progress over the last ten years regarding solar farm stations as well as horizontal axis wind turbines there has no new Up-Stream-Power-Station been designed and installed so far.

AIII-6.2 Physical basics

AIII-6.2.1 Energy content of the wind

The following section will be used to mathematically explain where the energy in the wind comes from and what factors it depends on.

Power is defined as:

$$P = \frac{E}{t} = \frac{1}{2} \cdot A \cdot \rho_a \cdot v^3 \qquad (1)$$

With
E: kinetic energy
A: area
ρ_a: specific density of the air
v: wind velocity

Therefore, it is also proportional to the cube of the wind speed, v^3.

From figure 6.2.1, it can be seen that the power output per m^2 of the rotor blade is not linearly proportional to the wind velocity, as proven in the theory above. This means that it is more profitable to place a wind turbine in a location with occaSional high winds, than in a location where there is a constant low wind speed. Measurement at different places shows that the distribution of wind velocity over the year could approximate by a Weibull-equitation. That means that at least about 2/3 of the produced electricity will be earned by the upper third of wind velocity.

From a mechanical point of view, the power density range increases by one thousand for a wind speed change of just 10 m/s, thus producing a construction limit problem. Therefore, wind turbines are constructed to harness only the power from wind speeds in the upper regions.

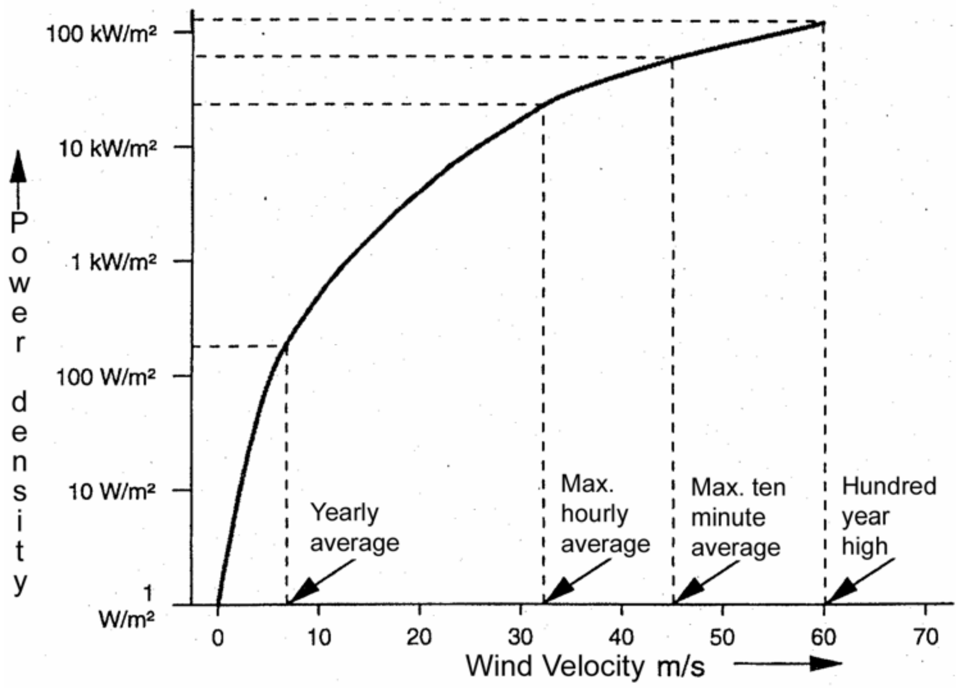


Figure 6.2.1: Relationship between wind velocity and power output (yearly average valid for Germany)[37]

AIII-6.2.2 Power coefficients

There is now the question of how much of the energy in the wind can be transferred to the blade as mechanical energy.

Betz' law and Cp

Betz' law states that you can only convert a maximum of 59% of the kinetic energy in the wind to mechanical energy using a wind turbine. This is because the wind on the back side of the rotor must have a high enough velocity to move away and allow more wind through the plane of the rotor.

The relationship between the power of the rotor blade P_R and the maximum power P_{Rmax} is given by the power coefficient c_P;

$$P_R = P_1 - P_2 = c_p \cdot P_{R\max} \quad (2)$$

[37] **This figure is taken from [93Kle, p241ff] and translated from German to English**

The maximum power coefficient is determined through the ratio v_2/v_1 and setting the derivation to zero.

$$c_{pmax} = \frac{16}{17} = 0.593 \qquad \text{with} \qquad v_2 = \frac{1}{3} \cdot v_1$$

Therefore, an ideal turbine will slow down the wind by 2/3 of its original speed (Betz' law).

The issues discussed in the theory can be summed up and related to the design of a wind energy turbine, by the so called Cooking recipe:

- A high aerofoil form ratio leads to a high Tip-speed ratio and therefore, a large power coefficient c_p.
  ⇒ Modern turbines with a good aerodynamic profile rotate quickly.

- Simple profiles with smaller profile form ratios have a small Tip-speed ratio. Therefore, the area of the rotor radius that is occupied by blades must be increased in order to increase the power coefficient.
  ⇒ Slow rotating turbines have poor aerodynamic profiles and a high number of blades.

- The profile form ratio and the tip-speed ratio have a considerably greater influence on the power coefficient than the number of blades.

- The quality of an aerofoil in respect to a high speed turbine, has an inferior significance.

AIII-6.3 Technical design of wind turbines

AIII-6.3.1 The classic design

The details of a classic design, also called the Danish design, because this is where its history lies, are shown in figure 6.3.1. The main aspect of the classic design is the split shaft system, where the main shaft turns slowly with the rotor blades and the torque is transmitted through a gearbox to the high-speed secondary shaft that drives the few-pole pair generator.

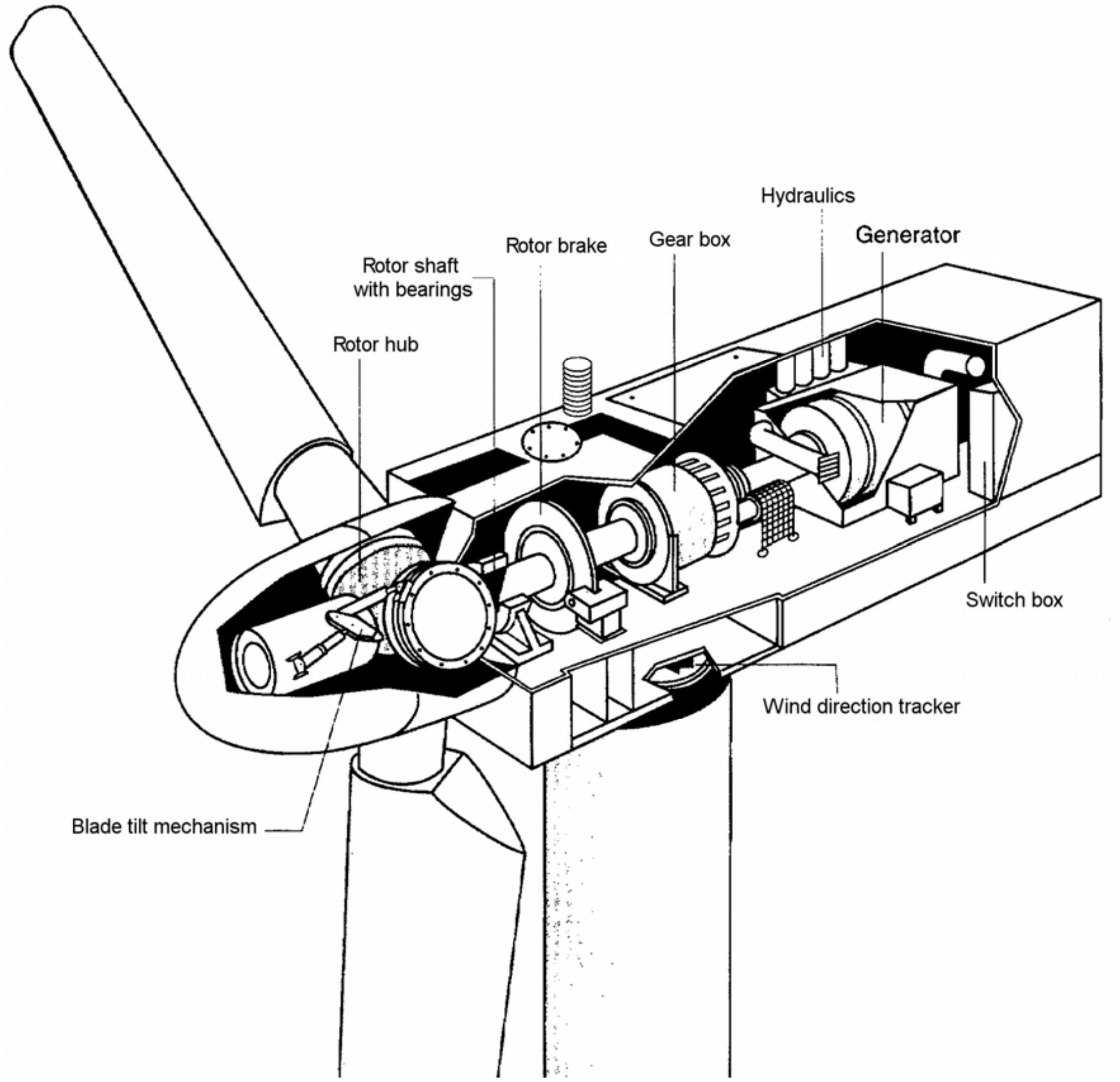


Figure 6.3.1 - The classic design

The transmission of torque to the generator is shut off by means of a large disk brake on the main shaft. A mechanical system controls the pitch of the blades, so pitch control can also be used to stop the operation of the turbine in e.g. storm conditions. The pitch mechanism is driven by a hydraulic system, with oil as the popular medium. This system needs almost yearly maintenance and constant pressure

monitoring, along with the gear box which is lubricated with oil. For constructions without a main brake, each blade has its pitch angle controlled by a small electric motor.

Wind speed and direction measuring apparatus are located at the back of the hub head. A rack-and- pinion mechanism at the join of the hub and the tower, allows the hub to be rotated in to the wind direction, and out of it in storm conditions.

AIII-6.3.2 The design without gearbox

Some companies e.g. the German company Enercon, design another turbine type, without gearbox. The scheme of such a turbine is shown in figure 6.3.2, where the main design aspects can be clearly seen.

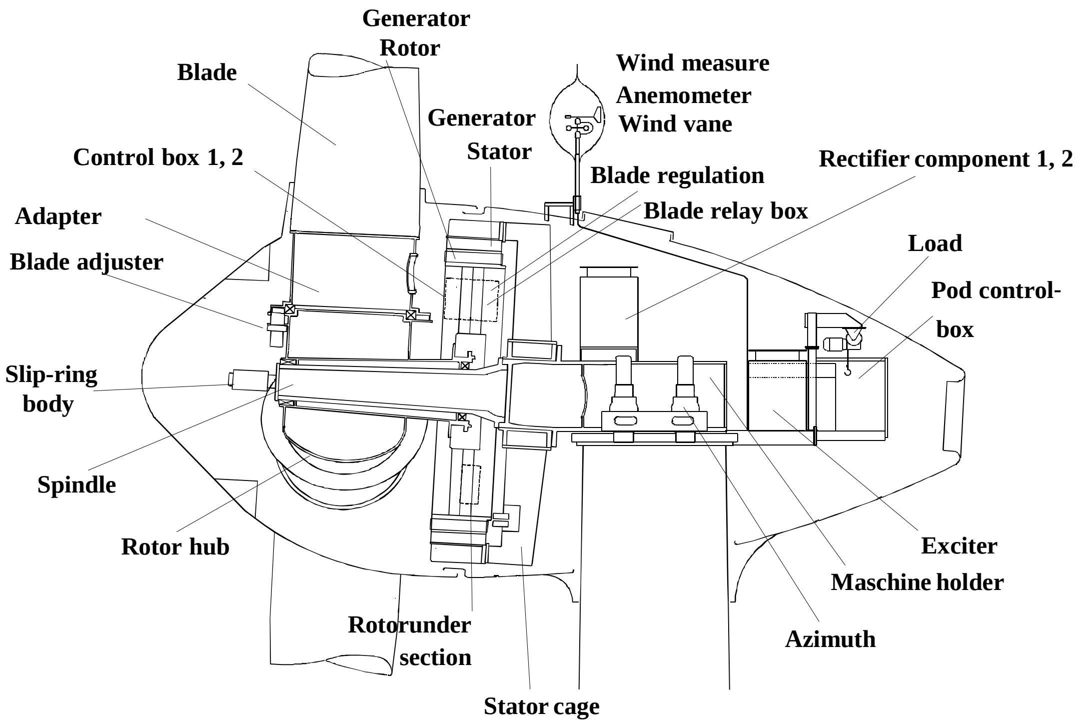


Figure 6.3.2: The design without gearbox (Enercon E-66)

This design has just one stationary shaft. The rotor blades and the generator are both mounted on this shaft. The generator is in the form of a large spoked wheel with e.g. forty-two pole pairs, around the outer circumference and stators mounted on a stationary arm around the wheel. The wheel is fixed to the blade apparatus, so it rotates slowly with the blades. Therefore, there is no need for a gearbox, rotating shafts or a disk brake. This minimising of mechanical parts simplifies the maintenance and production of the turbine.

The whole system is automated; pitch control and hub direction are controlled by a central computer, which operates the small directional motors.

AIII 6.3.3 Aspects of design and development

There are several critical aspects of a wind turbine that need to be considered in the design phase, to ensure the turbine will be economic and durable.

The tower:

In principle, the tower needs to be as tall as possible, because the wind speed increases with height. However, the height is limited by costing issues; an increase in tower height of 10m costs an extra fifteen thousand Dollars, and a tower height of over 100m requires an aircraft-warning beacon, which is again so expensive.

Heat energy:
Large turbines (>1MW), have an average generator efficiency of 98%. Heat is also generated in the mechanical parts of the machine including the bearings and the gear box. This means that around 40kW of power are lost to the generator heating up during operation. This heat energy needs to be controlled to prevent damage to the machine parts. A large fan system is mounted in on the back side of the hub of a turbine and used to draw cool air through the hub and remove the heat energy emitted during operation.

Control and Monitoring:

The following aspects of a wind turbine need to be controlled and monitored to ensure effective operation of a wind turbine within the legal limits.

- By large turbines; vibration levels
- Speed of rotation and the pitch angle, of the rotor blades
- The natural wind speed and direction
- The voltage and frequency of the electricity produced
- The output phase angle compared to the grid phase angle
- The consistency of the electrical power output
- The acquisition and storage of electrical signals
- Signal conversion equipment for the directional motors
- Rotational speed at night, to reduce the noise levels, because the noise is proportional to the blade-tip speed to the power six.

Mechanical stability:

The following forces affect the stability of the mechanical system:

- Gravity
- Centrifugal forces on the rotor blades
- Pressure changes on the blade due to the shadow effect the tower creates
- Stochastic power output of the turbine due to wind energy levels continually changing
- Resonance of the blades

Wind direction set-up:

A wind turbine can be designed to face in to the wind (windward), or away from it (leeward). A leeward turbine has the advantage of being self orientating, but the disadvantage of the tower disturbing the wind velocity profile, before the wind has reached the plane of the rotor blades. The pressure and speed differences experienced by the blade as it passes the tower, result in stresses on the hub, which need to be alleviated by use of an extra mechanism in the hub to allow the rotor blades to move out of their usual plane of rotation.

AIII-6.3.4 Technical figures of two modern wind turbines

The largest market introduced machine up to the year 2002, is an offshore 3.6 MW turbine from the company GE Wind with gearbox and a 2.0 MW turbine from the company Enercon without gearbox. Machines for the 5 MW class are at the stage of development at the end of the year 2004. A prototype 4.5 MW turbine was erected by the company Enercon in October 2002 (E-112) and another one with rated power of 5 MW has been erected by the company REpower Systems (REpower 5M) in September 2004.

Table 6.3.4 gives an idea of the size of the common features of prototypes of wind turbines. A Classic and an advanced design machine have been chosen to show the different operation of their generators.

Table 6.3.4- The technical figures of two different designed prototypes of multi-megawatt wind turbines

	Enercon E-112	REpower 5M
Design	without gearbox	with gearbox
Hub height	124 m	100 - 120 m (onshore)
No. Of blades	3 blades	3 blades
Rotor speed	8-13 rpm	6.9 -12.1 rpm
Rotor diameter	114 m	126 m
Material of blade	Fibreglass (reinforced epoxy)	Fibreglass (reinforced epoxy)
Blade regulation	Pitch	Pitch
Rated power	4.5 MW	5 MW
Transmission ratio of gearbox	None	i= approx. 97
Generator	Multi-pole	few poles
Grid connection	Via frequency converters	Via frequency converters

AIII-6.4 Connection to the electrical grid

The main electrical grid has a constant frequency e.g. of 50 Hz or 60 Hz and a constant phase angle. Therefore, a wind turbine must produce electricity with the same constant values in order to be integrated into the main grid.

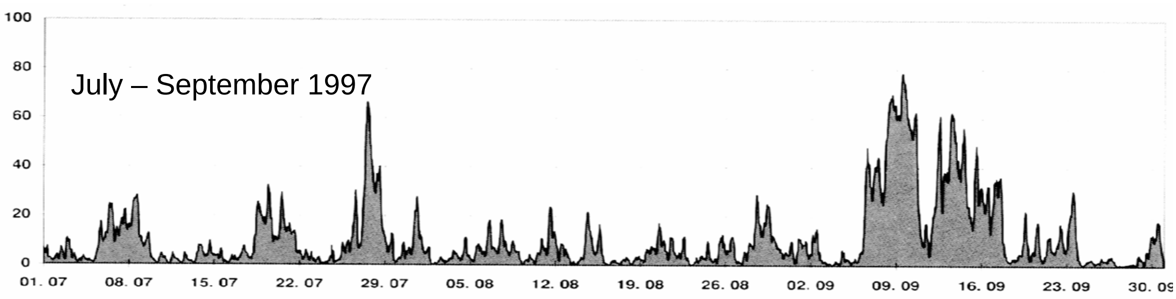
The input energy of a wind turbine is proportional to the wind speed, but the wind speed is never constant. Each wind speed has a corresponding rotor rotation speed, at which the maximum power is produced. This maximum occurs for different wind speeds at different rates of rotation. However, the rate of rotation must be held constant in order to achieve the required constant output frequency or the wind turbine has to be connected to the grid by doubly fed asynchronous generator or by electronic frequency converters.
A small turbine can be connected directly into the grid network at 0.4 kV. When the wind turbine is integrated into the grid network, there must be no voltage change, voltage oscillation or flicker experienced in the homes on that network branch. The loss of voltage due to resistance in the cabling can be avoided by increasing the diameter of the cables. It is often required that a

new network branch is constructed and linked to the transformer, in order to reduce the voltage disturbances. This increases the installation costs of the turbine.

Megawatt turbines cannot be connected to the grid at the 0.4 kV stage, but have to be connected in at 10-30 kV, which is the usual level of the city electricity share distribution. In remote areas, where a 30 kV connection is not established, the connection must be created and financed by the wind park developers. Wind parks with a lot of Megawatt turbines can also be connected into the electrical grid at the 110 kV level.

As mentioned earlier the maximum power output is obtained only in few hours during the year. Figure 6.4a shows a typical load distribution, measured in Germany.
With larger wind energy installations in future this uneven distribution leads to the need of higher regulation capacities by conventional power systems.

Percent of total capacity (28 MW)



Percent of total capacity (28 MW)

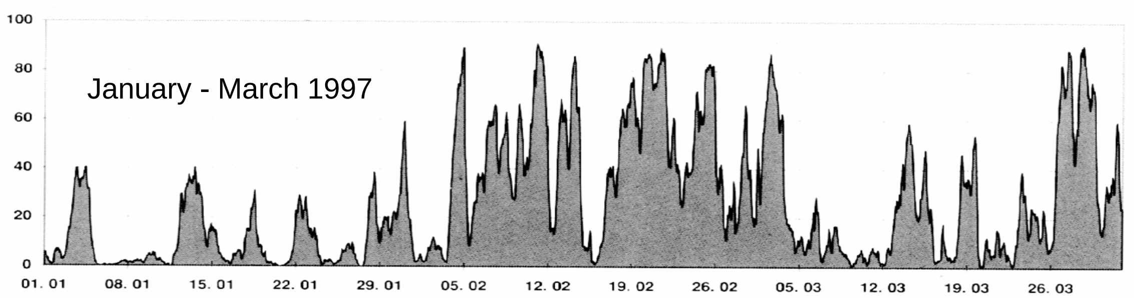


Figure 6.4.- Load Distribution – Measurement (Germany)

Grid connection of offshore wind farms poses a technical and economical challenge to wind turbine and grid operators. In the initial phase, the still quite limited capacity of early pilot farms enables using a conventional three-phase AC connection to the onshore grid system which is a well known technology and inexpensive (currently: 175 kV, tendency in the future: 240 kV).

Greater capacities and remote offshore sites make it technically difficult to connect offshore wind farms to the mainland grid by using AC undersea cables. Losses, reactive power production and limited capacity of the sea cables may become important in the future. High-voltage direct current transmission to land could be a solution but it is technically complicated and expensive.

At the moment there is no comprehensive plan for connecting offshore wind farms to the mainland grid and also the pipeline route is not clarified. One possibility is bundling of several wind farms to clusters.

To connect the offshore wind farm to the onshore grid an internal grid is necessary. The produced power has to be feed to an offshore transformer substation. Wind turbines are connected to it via undersea cables by a voltage of about 30 kV. After stepping-up to the transmission line voltage, the power is conveyed to shore.

AIII-6.5 Use of wind energy

AIII-6.5.1 World-wide status

In the nineteen eighties, it was the USA that took the lead in establishing wind farms. They set over 10,000 turbines into operation, each generating between 80–200 kW. In Europe it was Denmark that were the main pioneers of wind energy. Today in the twenty-first century, Germany has taken the world lead, producing about a third of the worlds wind produced electricity.

Many governments have began to produce initiative schemes to increase the economic feasibility of wind turbines. Some initiatives used include, paying more for wind produced electricity, and providing a proportion of the initial construction costs. Governments of industrial countries, or those with a high power consumption, are eager to promote wind energy, because it is environmentally clean and sustainable and limits the need for fossil fuel usage. This attitude has lead to seven countries leading the way in world wind energy usage, as seen in table 6.5.1

Table 6.5.1: World wind power production[38]

Land/Region	Total installed rated power up to the end of 2003 [MW]
World total	**40300**
Germany	14600
Spain	6400
USA	6400
Denmark	3100
India	2100
China	600
Norway	100
GUS	30

The world total is about 40300 MW, this means that a few countries in Europe and USA supply 76% of the world's wind power. The development in Europe has been aided by the European government who have set wind energy usage targets to be met by 2010. The main manufactures of wind turbines are located in Denmark, Germany and the USA, thus other lands rely on importing the required technology.

AIII-6.5.2 Investment and operation costs

The costs involved in installing a wind turbine vary depending on the design, size and chosen location of the new turbine. The infrastructure costs can be minimised by constructing wind parks, where a number of new turbines are installed on the same sight. An example of the investment costs for a wind park in Germany is shown in table 4.

[38] **This statistic is taken from [04DEW]**

Table 6.5.2: The investment costs of Amesdorf and Wellen wind park in Germany, (Status: Nov. 2001).

	INVESTED COSTS [Million Euros]	PERCENT OF TOTAL
Wind Park (ten 1.5 MW turbines) incl. transport, assembly, cabling, starting-up, grid connection and reinforcement, infrastructure.	15.8	83%
Technical planning, foundation soil analysis, survey, and grid connection fee.	2.0	10%
Commission, funding during phase of construction, interest risk.	0.1	1%
Compensatory measures during phase of construction.	0.3	1.3%
Raising of capital.	0.5	3%
Financial, contractual and fiscal consulting.	0.3	1.3%
Grand total	19	100%

The money invested in an average wind park depreciates over about a ten year period. During this period, the set-up and installation costs are high, along with the loan repayments and insurance costs. After this period, the costs then decrease. Over the next ten years, a financial return can then be made on the investment, when the price for the electricity per kilowatt hour is set at a high value by the government. This means it is economic to ensure the durability of the installed turbines, so maintenance costs after the ten year period are kept low and the investors can receive a good return on their investment.

The above example of investment costs in Germany is non-transferable to other countries. Especially the employee's wages and the structure of financing wind farms are quite different. Nevertheless power generating by wind turbines in developed countries with existing electrical grid and sufficient installed power, costs three to four times in comparison to power generation by conventional power stations.

AIII-6.5.3 Environmental aspects

Wind energy is a renewable energy source; therefore it holds many advantages over the fossil fuels, which have diminishing reserves. Wind energy is clean in regard to toxic emissions. Therefore, it does not add to Global warming or Acid rain problems.

The wind turbines can affect the environment in aesthetic and human intrusive ways. This is because they must be sited in prominent locations and through the nature the rotation of their blades; they produce optical distortions i.e. flickering shadows, and a humming noise. The land required for the sighting of a wind park can be considered large, if all the access routes are also taken into consideration. However, they very rarely require the resettlement of communities, which is a problem associated with e.g large Hydro-Electric-Power stations. The danger to birds of the rotating blades has been questioned, but it has been found that the birds change their flight paths to avoid the blades. It has also be questioned whether the reduced wind speed at ground level, affects the growth of flora. This is answered by the observation that many wind parks have animals grazing between the turbines.

AIII-6.6 Research and Development Needs

According to the first report of the project "Wind Energy Thematic Network" founded by the European Commission, some aspects of the R&D needs are described below[39]:

AIII-6.6.1 Environmental & Social Impacts (e.g. enhancing local incentives by developing participation models)

- Methods to integrate wind turbines visually in to the landscape
- Reduction of noise impacts
- Mitigating impacts on bird populations, habitats and flight paths
- Turbine design regarding life cycle analysis
- Analyse social effects like local employment, investment, taxes etc..

AIII-6.6.2 Wind Turbine & Component Design Issues **(e.g. basic research in aerodynamics, structural dynamics, structural design and control)**

- New materials with higher strength like carbon fibre for the blades
- Feasibility studies of new wind turbines concepts and innovations
- Integration of demand site requirements in the design of turbine, e.g. electrical control system interaction with grid requirement

AIII-6.6.3 Testing, Standardisation, & Certification **(e.g. common accepted certification procedures for wind turbines and wind farms)**

- Identification of standards lacking, and initiation of appropriate actions for new standards
- Standards for service and maintenance concepts
- Guidelines and standards describing the steps in project development

AIII-6.6.4 Grid Integration, Energy Systems & Resource Prediction (e.g. forecast of wind resource)

- Development of scenarios for redesigning the grid system with high wind penetration
- Increasing both: power quality and consistency
- Energy management and storage systems for stand alone applications

AIII-6.6.5. Operation & Maintenance **(e.g. advanced condition monitoring)**

- Development of early failure detection and condition systems
- Development in preventative maintenance
- Standardisation of components for easy replacement
- Certification of service and maintenance concepts

AIII-6.6.6 New potentials **(e.g. in complex terrain and remote areas where satellite technology can be used, among others, in the formulation of wind atlases – showing the wind resource)**

[39] **Facts are taken from [04EWE]**

- Offshore resource assessment
- Market surveys of developing country markets
- Cold and icing climates resource assessment

AIII-6.6.7 Offshore Wind Technology **(e.g. research into the control and efficiency of very large wind farms and more cost effective foundations, transport and installation techniques)**

- Monitoring of environmental impacts (effects on birds, effects of noise and vibration on marine life etc.)
- Development of deep water foundation structures
- offshore meteorology
- Design studies of systems rated above 5 MW
- Special designs of systems and components for transportation, erection, access and maintenance of offshore wind turbines
- Development of direct drive generators using permanent magnets
- Investigate the use of energy storage
- Grid connection to mainland and onshore power transmission to the consumers
- Improve corrosion protecting systems regarding the offshore conditions

AIII-6.6.8 Megawatt and Multi-Megawatt Wind Turbines **(e.g. application of new materials with improved strength-mass ratio and development of lighter components)**

- Fundamental wind turbine design research
- Transport requirements for blades
- Development of test facilities

In addition to these aspects there are a lot of R&D Needs by operating and market introduced wind turbines, e.g.:

- Better state of knowledge of the dynamic forces on the drive train
- Improvement of the availability of gear boxes
- Optimisation of control units and control systems
- Development of central lubrication systems

AIII-6.7 Outlook

The wind energy market has grown because of the environmental advantages of harnessing a clean and inexhaustible energy source and because of the economic incentives supplied by several governments. However, energy is required from other generation methods during the building phase of a new turbine, so in this period, Greenhouse gases and air pollution will be added to. If the life cycle of a wind turbine is looked at, more pollutants are saved on during operation, than are emitted during the building phase.

A wind turbine is not a self-sustainable power station. This means that back-up power generation is needed at the times when the turbine is unoperational. This back-up is nowadays supplied by the established fossil fuel power stations. If the number of wind turbines increases in the long term to produce about 10 % of the electricity, the need for extra investment in the back-up generation systems will arise, in order to maintain a stable electricity grid system. These additional investments will need to be met by the wind energy conversion companies.

However, wind energy is still one of the most important renewable energy resources for the future, because it can be harnessed in a clean and unexhaustable manner, through the application of technically advanced, and efficient machinery.

There are a lot of R&D needs, a challenge for scientists, engineers and economists. Let´s start!

AIII-6.8 Bibliography:

93Kle Kleemann, M. and Melіß, M.: Regenerative Energiequellen, 2.Auflage Springer-Verlag, Heidelberg, (1993)

04DEW Wind Energy Use in Germany; http://www.dewi.de/statistics.html

04EWE EWEA, The European Wind Industry: Strategic Plan For Research & Development, First Report: Creating the knowledge foundation for a clean energy era