AT9200630

Collaborative Paper

Future Prospects for Renewable Energy Sources in a Global Frame

Peter Lund

CP-92-3
June 1992

IIASA International Institute for Applied Systems Analysis □ A-2361 Laxenburg □ Austria
Telephone: +43 2236 715210 □ Telex: 079 137 iiasa a □ Telefax: +43 2236 71313

Future Prospects for Renewable Energy Sources in a Global Frame

Peter Lund

CP-92-3
June 1992

Peter Lund is from the Helsinki University of Technology,
SF-02150 Espoo, Finland

IIASA International Institute for Applied Systems Analysis □ A-2361 Laxenburg □ Austria
Telephone: +43 2236 715210 □ Telex: 079 137 iiasa a □ Telefax: +43 2236 71313

Foreword

Consensus exists that further environmental pollution and the resulting climatic changes could be prevented if energy systems emissions are significantly reduced. Scientists and politicians worldwide are studying ways for the transition from current energy systems which are mainly based on fossil (carbon) fuels to systems with a non-carbon base. Four directions are known to achieve such reductions: (1) energy conservation and efficiency improvements; (2) replacement of high-content-carbon fuel (coal, crude oil) by low-content and more effectively used fuels (natural gas); (3) wide introduction of non-carbon fuels or technologies; and (4) CO_2 removal from flue gas. Renewable energies are often considered as one of the major possible contributors to the solution or, at least prevention, of global warming.

However, there are several controversial and negative points which diminish the importance of the renewable energy options. These are: low density of natural energy fluxes which require large and expensive devices to trap and convert those energy forms into useful energy: strong dependence on local conditions; large fluctuations over daytime or seasons; and slow increases in fossil fuel prices in the future (if no special environmental constraints are imposed). Therefore, it is highly important to have a balanced and reasonable view on the real contribution of renewable energy sources towards solving global energy/environmental problems.

Here, the author makes an attempt to approach the problem of implementing solar and wind technologies in a global frame. He spent several weeks at IIASA in late 1991, working on a more detailed and transparent analysis of future prospects for renewable energies This paper is a good supplement to the issue of renewable energies for the Global Energy and Climate Change Report (SR-92-04), recently finalized at IIASA and which will be available from IIASA's Publications Department later this year.

Yuri Sinyak
Principal Investigator
Global Energy and Climate Change

Contents

Future Prospects for Renewable Energy Sources in a Global Frame

Peter Lund

1. INTRODUCTION

1.1 Our Global Problem

Energy is one of the most important natural resources that affect directly the welfare of mankind. Without energy, present industrial and societal activities would not be possible. Most of both the regional and global environmental problems are also interrelated with energy. More than 85 per cent of all primary energy stems from abundant fossil-fuels with harmful emissions [Smith-Morris, 1990]. Of largest concern are the anthropogenic carbon dioxide emissions that may ultimately lead to a climate change if not limited. As a whole, the energy sector contributes some 50 per cent of all greenhouse gases [Intergovernmental Panel on Climate Change, 1990]. Of all the constraints imposed on energy, the environment will probably be the most influent factor that will reshape the criteria of energy planning in the future.

What makes the situation even worse is the fact that the global primary energy demand is still showing a steady growth, i.e. on average 2.2% per year in the 1980's [Smith-Morris, 1990]. A larger share of this increase is coming from the less developed countries (abbreviated LDC) with high population growth rates and aggressive industrialization policies. Most of the new commerical energy in these countries is based on fossil fuels [Levine, 1991]. Extensive use of non-commerical energies in some LDCs, especially in form of fuel-wood, has a very negative impact on the environment because of deforestation and erosion. Developing countries use energy per person only 1/10th of that in industrialized countries [Smith-Morris, 1990]. However, at the same time, the share of world's population in developed countries is less than one quarter of the world's population and this proportion is still decreasing due to much lower birth rates.

The higher fertility and increasing per capita energy demand will shift the focus of energy-related enviromental problems from early next century onwards to the less developed countries. It is now clear that a solution to the global climate change question will necessitate a global energy perspective including the LDCs. The development in the Third World is very critical to long-term energy projections as also to the stabilization of the degradation of nature.

The United Nations IPCC (Intergovernmental Panel on Climate Change) has recently estimated that an atmospheric stabilization would require a 60 % reduction in human-made CO_2 emissions from 1990 levels. Such an ambitious goal would mean major changes in present-day energy practices both in the industrialized and less developed countries: the CO_2 emissions in the industrialized countries must drop by 75-80 % and in LDCs by 25-30% from their present levels [Sinyak, 1991]. The required level could be reached through stringent controls by the middle of the 21st century.

A more sustainable energy future with decreasing CO_2 emissions may be realized only through a radical mix of technology options and policy guidelines. This could include more efficient energy end-use and improved fuel economy, fuel shift from coal to natural gas, increased use of carbon free energy sources, disposal of carbon dioxide as well as reforestation. Not a single measure alone but a mix of several measures together in parallel is needed for a positive outcome [OECD, 1989]. The present economic and social goals, especially those of the less developed countries, put major uncertainity on any global policy plan trying to implent these technologies into practice. Indeed, profound economic reforms, e.g. incorporating the real costs of an energy technology, or energy source, over its life-time and fuel cycle on the society into the pricing system of energy, are necessary to make a global policy effective or even possible. Furthermore, the role of the Third World in securing a sustainable global habitat cannot be overemphasized. Active technology transfer from the industrialized to the less developed countries could secure an increased and balanced growth of wellfare in this part of the world.

1.2 The role of new energy sources in a sustainable energy future

The potential of new energy sources has often been neglected or sometimes much overestimated in formulating the energy future. They form in any case an important base for environmentally benign energy production in the future as they are inherently emission free. New or renewable energy sources produce today some 5 % of world's primary energy [Smith-Morris, 1990]. Renewables excluding hydropower make up some 1% of the total OECD electricity capacity [IEA, 1990]. Apart from hydropower and some biomass, other new energy sources such as solar or wind energy have today only a negligible contribution on a world scale. The resource potential is, however, very large and ample, but only a minor fraction of this could be utilized due to the low energy density and variability of these sources. Also, solar and wind have shown an impressive record in terms of technology improvements and reduced costs since the late 1970's. If this progress would continue, even with a slower pace, the commercialization of some of the new energy sources may start in the near future.

Large human and physical resources are needed to build sustainable energy systems. Appropriate environmental expenditures may need to be increased on the order of 2% of GNP over normal energy investments [Sinyak, 1991]. Optimum resource allocation will be important for maximum benefits from climate stabilizing investments. A good methodological approch to get a comprehensive insight on the environmental effectiveness is a total energy cycle analysis. In such an analysis, the life-time emissions of a technology are considered over each energy production stage (fuel extraction, construction, operation). Combining the total emissions with energy production figures and/or investment needs, an indicative index of effectiveness can be obtained (kg CO_2/kWh x kWh/\$=kg CO_2/\$). As a first-order approximation of a total fuel cycle analysis, a traditional net energy analysis with a weighted emission factor for the input energy could be used. The net energy ratios of various energy technologies as such may already give an indication on the environmental effectiveness.

New energy sources do not produce any greenhouse gases during operation. Even over the total fuel-cycle, the emissions from renewables are insignificant compared to the best projected fossil-fuel power plants: for an IGCC power plant we have 751, for natural gas 484, and for renewable electric production 3-8 tons CO_2/GWh [OECD, 1989]. For net energy production, latest solar and wind energy technologies show pay-back times in the range of 2-3 years [Winter, 1988], i.e. comparable to any other existing energy sources.

There are many other factors than those above that influence the usefulness and possibilities of technologies in the long-term run in mitigating the climate change. Access to resources and resource requirements, life-time and reliability, market capability and manufacturability, institutional barriers, etc. are all critical factors. The solution to the energy problems depends in the first place on the technologies that are available and the rate at which they evolve. The rate at which new technologies penetrate the world market is difficult to predict - some indication may be obtained from the evolution of present energy technologies in the past. These show that the world market share of a single energy technology may increase or decrease no more than 1-2 % per year, reflecting the large inertia of the energy infrastructure [Häfele, 1981]. Energy investments are typically made with a time horizon of over 30 years life-time.

The potential of new energy sources has been assessed in the past by several studies. These have ended up with potential figures of a few per cent of world primary energy in year 2020 [Häfele, 1981; WEC, 1989]. A recent scenario study for stablizing the global climate change estimates that some 10-15% of all energy could be derived from solar technologies by the mid 21st century [Lashof, 1989]. Sinyak (1990) has presented a range of global energy scenarios in which the share for intermittent technologies in year 2050 varies from 8% to 24%.

The objective of this study has been to evaluate the possibilities of some new energy sources (solar, wind) in the future world energy supply. We intend to prepare future projections accounting for <u>limitations</u> in infrastructure, time, and material inputs. One underlying <u>assumption</u> in the analyses is that new technologies will see an early market introduction in the near future which would continue up to year 2020. During these 30 years, there will still be technological developments leading to a much better manufacturability, mass production, and hence reduced costs. In year 2020, the industrial and economic infrastructure of new energy sources would be mature for a major penetration into the world energy market starting to substitute existing energy sources mainly for environmental reasons. This scenario will be supported by more factual information and data in the following chapters.

Each new energy technology will be handled separately, (as these represent actually quite different technologies and should not be just simply homogenized in the analyses as often happens)

2. NEW ENERGY TECHNOLOGIES

2.1 Technology status

This paper concentrates on a major sub-area within renewable energies namely solar thermal, solar electricity, and wind power. All of these can be characterized as intermittent, i.e. they have on average predicatable characteristics, but available power cannot be predicted at any defined time in the future. Thus, these energy sources may be viewed mainly as fuel saving options. Through energy storage or fuel back-up power availability can be increased.

In solar thermal power systems, concentrating mirrors are used to heat up a heat transfer fluid that produces electricity in a conventional turbine. Photovoltaic systems comprise of solar cells based on semi-conductors that convert light directly to a DC current. Through an inverter this electricity may be converted into an AC current. Wind power systems utilize typically a number of wind turbines that are grouped into wind farms. A commerical wind turbine rotates usually around a horizontal axes and has two or three blades. A solar heating system comprises black-painted solar collectors that effectively convert solar radiation into useable heat. All of these technologies are suitable for centralized or decentralized energy production. The unit-size is often small and through combining many such units together, a desired performance rate can be achieved. A very good modularity may thus be obtained which may be an important attribute in the future.

The basic technology for utilizing solar and wind energy already exists. There has been a tremendous progress during the 1980's in making these technologies more efficient, reliable, and cost-effective. The cost of produced energy has dropped by a factor of 3-4 during the last 10 years and plant availabilities are exceeding those of conventional power plants [Weinberg, 1990]. In a favourable climate, the costs would be almost competitive - in a global scale the economic breakthrough is still further off. For instance, in California the unit life-time price of new wind generated electricity is $70-80 per MWh and for solar thermal electricity $90-100 per MWh [EPRI, 1991]. As a result, also the resource requirements per unit have decreased.

This may be a surprising result as the markets for these technologies are small and the R&D efforts compared to other energy technologies are still relatively modest [IEA, 1990]. A reason to this success may be found in the size of new technologies : to install 100 MW of power one would need only one conventional power plant, wheras to realize this nominal power requirement through wind technology one needs 1,000 wind turbines each 100 kW, or 2 million photovoltaic modules each 50 W, etc. This gives an important advantage over conventional large power plants: a more rapid advancement on the learning curve of a technology resulting in cost reductions. Also, it may be worthwhile to observe that solar or wind has not really yet been able to take advantage of the benefits from the economies of scale as the markets are small. Entering a stage of mass-production could bring the costs down to a competitive level indicated recently by major manufactures [Johansson, 1989].

Eventhough there exists a growing market for these technologies, there has so far been little incentives to convert into a mass-production format as the markets have been quite uncertain. There are niche markets that are very important to industrial growth. For instance, the photovoltaic industries have grown from mid-80's by some 25 % per year through an increasing demand of consumer products and remote power applications [Lund, 1990]. A 10-20% per year increase in wind power manufacturing capabilities has also been witnessed [EWEA, 1991]. Notwithstanding the photovoltaics, the markets for new energy sources have been unstable in the 70's and 80's showing ups and downs that are sometimes devastating when creating new industrial infrastructures. The markets have since some years, however, shown a much better and smoother behaviour, to which the increased professionalism within the industries may have had an important contribution, too. The niche markets will in general serve as a base of growth perhaps until the end of this century, but thereafter strong penetration to utility markets has to take place in order to maintain the industry growth rates of the 80's and 90's. This early utility market is a necessity to bring new energy sources to a bulk (world) energy market in year 2020. There are signs for utility and manufacturer alliancies to fill this "gap" in the coming years [Iannucci, 1991].

Table 1 summarizes the present status of the utilization and production of solar-based technologies [Blum, 1989; Clarke, 1991; Kearney, 1991; Lund, 1990]. The share of new technologies of all world primary energy in year 1991 corresponds to some 0.03-0.04 %. Some 70-75 % of all solar and wind energy is produced in the United States. Europe, the U.S., and Japan are the leading edges in developing new energy technologies today.

New energy technologies should lend themselves well to mass-production as the energy system itself is the final product of the process. The industries in this field resemble more electronics (photovoltaics) or light metal or manufacturing industries (wind, solar thermal, solar heating) than typical energy-related heavy industries. Solar and wind energy systems are often a side-line stream or shadow-market of a larger main industry and don't as such serve an energy sector. Because of the small unit-size of new energy technology systems, most of the production could be handled through computer-integrated-manufacturing techniques enabling mass production and lowering of manufacturing costs (economies of scale). This applies especially to thin film photovoltaics [Johansson, 1989].

Table 1
Estimated commercial world-wide utilization
of new energy sources in year 1991

Technology	Energy per year	Installed capacity (nom)	Production per year
Solar thermal power	1 TWh	300 MW	50 MW
Photovoltaics	0.5 TWh	300 MW_p	50 MW_p
Wind power	3 TWh	2000 MW	400 MW
Solar heating	15 TWh(th)	3×10^7 m^2 15,000 MW(th)	2×10^6 m^2 1,000 MW(th)

2.2 Outlook of future characteristics

Present and estimated future system costs for installed power are shown in Table 2a [EPRI, 1991; Flavin, 1989; Johansson, 1989; Lund, 1990; SERI, 1990]. The cost figures include in addition to the generating devices all balance of system costs but exclude the land. The generating equipment itself accounts for 60-70 per cent of the total costs. As long as the share of intermittent technologies of the total electricity or energy supply remains modest which is probably the case prior to year 2020, land or additional larger energy infrastructure investments will be insignificant. How e.g. the electric network or transmission stations need to be expanded if a large share of renewable generating capacity is added is difficult to assess accurately, but that would in any case increase the costs. Thus, the cost projections after year 2020 should be considered indicative. In all, the major cost reductions are expected to come from scale-up to mass production as also to some extent from performance improvements.

Solar as well as wind energy has a very small, or no, power component and produces as such only energy. Thus, production and consumption fall timewise often apart and as a result some additional power supply or energy storage is needed to compensate for the mismatch. For grid-connected electrical systems, the utility may be used up to a certain limit as a back-up and no additional investment is necessary. For higher shares of intermittent electricity, cheap gas turbines may be a viable option to provide power. Stand-alone systems in remote areas have no electrical grid to support it and a storage device or back-up power generator is needed. The same rationale applies equally to solar heating for which a water storage tank provides a satisfactory back-up. A more detailed discussion on the energy storage question and how its need depends on the fraction of the intermittent source is given in Chapter 5.1. A summary of the investment costs for the energy storage component and the back-up electricity costs is given in Table 2b [EPRI, 1989; Ogden, 1989; Schleicher, 1991, Winter, 1988]. Long-term storage includes large technical uncertainties and the cost figures shown here are mainly obtained from large-scale short-term storage applications with proper storage size but shorter storage time (e.g., pumped hydro, compressed air storage).

The performance, i.e. the energy yield, of an intermittent technology depends on the weather conditions, conversion efficiency, and system availability. Both the efficiency and availability values have increased over the last decade. Commercial conversion efficiencies are expected to still increase for all technologies, but most notably for photovoltaics. We have chosen here the ratio of the energy output to the nominal (peak) power as the performance indicator as this is less affected by the efficiency. Table 3 gives typical performance estimates for new technologies. The higher range of these values corresponds to good conditions. For the scenario analyses, average values are employed.

The capacity factor of new energy sources is typically in the range of 20-25%. Through storage or back-up power this figure may be increased. For instance, solar thermal power has been used in California with natural gas to give a capacity factor of about 50%. The numerical values for the energy storage requirement shown in Table 3 are only indicative, but good enough for the purposes of this study. A high total fraction of new energy technologies would require long-term energy storage or much back-up energy whereas for smaller fractions, short-term storage or a simple back-up, and in some cases even no additional compensation equipment, would be adequate. Table 3 gives also an estimate of how much back-up energy would be needed to exclude short-term or long-term storage requirements.

Table 2a
Projections of the total investment of new energy sources

	1990	2000	2010	2020	2030	2040	2050
Solar thermal power	\$3/W_n	2	1.6	1.4	1.2	1.1	1
Photovoltaics	\$7/W_p	3	2	1.4	1	0.9	0.8
Wind power	\$1.5/W_n	1.2	1	0.9	0.8	0.8	0.8
Solar heating	\$0.9/W_{th}	0.7	0.6	0.5	0.4	0.3	0.3

W_n=nominal (peak) capacity; W_p=peak capacity; W_{th}=thermal capacity

Table 2b
Investment projections for large-scale energy storage
($ per kWh of storage capacity excluding the cost of charging energy)

		1990	2000	2020	>2020
Heat storage	(short-term)	40	20	10	10
	(long-term)	2	1	0.5	0.5
Electric storage	(short-term)	140	100	30	20
	(long-term)	10	5	1	0.8
Hydrogen	(fuel)	2.5	1.5	0.5	0.3

Cost of back-up electricity ($ per produced kWh of electricity):
Gas turbine 0.06-0.07
Diesel generator 0.14-0.16

Table 3
Performance values used in the analyses

	Range of yearly energy output [kWh/W_p]	Average yearly energy output [kWh/W_p]	Energy storage short-term [Wh_e/W_p]	Energy storage long-term [Wh_e/W_p]	Back-up energy short-term [kWh/W_p]	Back-up energy long-term [kWh/W_p]
Solar th power	1.5-2.5	2.0	6	100	2.0	6.75
Photovoltaics	1-2.5	1.75	6	300	2.0	7.0
Wind power	1.5-2.5	2.0	6	100	2.0	6.75
Solar heating	1-2 400-800	1.5 600 (kWh/m^2)	5	200	1.5	7.25

Combining the data from Table 2 and 3 and including the maintenance costs, the projected price of produced energy can be calculated as shown in Table 4a. The cost figures for solar heating and photovoltaic technologies up to year 2010 include also small-scale short-term storage investments. For a mature technology (post-2020 period), the operation and maintenence costs are estimated as follows: photovoltaics \$2/MWh, solar heating \$5/MWh, wind \$6/MWh, and solar thermal power \$12/MWh [SERI, 1990]. A real discount rate of 6 % is used and for the system life-time 20 years until year 2020 and otherwise 30 years. For competitive large-scale bulk power production today, a price level of about \$50/MWh is required. This level is estimated to be reached in practice with all shown technologies after year 2020; wind technology seems to be closest to breakthrough pricewise. Some additional costs not shown here may arise from building electrical support infrastructures in far future (2040-2050).

The additional costs due to possible energy storage or backup are obtained from Table 2b and 3 as a product of the investment costs (\$/kWh_e), storage demand (Wh_e/W_p), and the annuity factor (6%, 20-30 years) divided by yearly energy production (kWh/W_p). For long-term storage, the yearly energy output is reduced by 25 per cent to account for storage unefficiencies. Table 4b shows the outcome of the economic calculations. Prior to year 2020, back-up power provides the most cost-effective means to improve the capacity availability of new energy sources. From year 2020 onwards, a separate storage component seems to indicate a better economics. If intermittent technologies could not then be supported anymore by the existing energy production infrastructure, which may be the case for a high fraction of new energy technologies in the energy supply, the storage may add in average some 20-25 per cent to, or in the worst case double (urban photovoltaics), the production price of new energy sources. Producing hydrogen fuel through electrolysis by new energy sources would add some \$30/MWh to the cost of produced energy given in Table 4a.

Table 4a
Cost projections for new energy sources without energy storage
(in units $/MWh)

	1990	2000	2010	2020	2030	2040	2050
Solar th power	131	87	70	61	54	49	45
Photovoltaics	348	149	99	70	44	39	35
Wind power	65	52	44	39	35	35	35
Solar heating	52	41	35	29	24	20	20

Table 4b
Price increase of new energy sources when large-scale short-term or long-term energy storage, or back-up system is added to improve the capacity factor
(in units $/MWh)

	1990		2000		2020		>2020		Back-up energy	
	short term	long term							short term	long term
Solar th power	26	**59**	13	**29**	7	**11**	7	**11**	6-12	**21-42**
Photovoltaics	30	**199**	15	**100**	8	**33**	5	**33**	7-14	**24-48**
Wind power	26	**59**	13	**29**	7	**11**	4	**11**	6-12	**21-42**
Solar heating	12	**31**	6	**16**	3	**7**	3	**7**	6-12	**29-58**

2.3 Policy implications for utilization in the 1990's

Some conclusions on the trends of new energy sources may be drawn from the near-term goals for their use in different countries. In general, several governments support new energy sources more effectively today than before, which may be considered as a signal that may trig off a more concerted effort to promote new technologies, and especially, their manufacturability. More profound policy changes in this direction may be possible due to foreseen international agreements in limiting the CO_2 emissions.

In the U.S. alone, optimistic projections for the late 1990's in wind and solar energy use are more than tenfold compared to those of the early 90's [SERI, 1990]. In Europe, a wind energy strategy calls for an almost tenfold increase in the next ten years [Clarke, 1991; EWEA, 1991]. These figures would imply over 30 % per year growth rates in the corresponding industries. Even in these cases new energy sources would play a very marginal role in the energy supply at the turn of the century.

Most of the solar thermal power capacity increase will take place in the U.S. and may double or even triple in the time period considered. The average growth rate of this sector is expected to be much smaller than that of the main stream new technologies, or, some 10 % per year. This could be explained by the restricted geographical utilizability of this technology.

The solar heating market is much more difficult to estimate as the size of the enterprises in this field is mainly small. The market in several countries showed instability and growth rates dropped in the mid-80s. The situation is now more stable, the credibility is better, and the public interest large. These factors could eventually give arise to a 5-6 % yearly growth over the 90's.

3. GLOBAL ENERGY DEMAND PROJECTIONS

The global energy demand trends and the level of environmental restrictions will much influence what percentage of the global energy production the new energy technologies may reach. As an important back-ground hypothesis, we assume here that a climate change stabilization in the spirit of the IPCC is globally strived for. This will first of all require large energy conservation measures which will probably be implemented prior or parallel to new energy production. The primary energy demand increase, if allowed, would take place in the less developed countries. Also, the importance of electricity will globally increase. The resulting global energy projection recently made at IIASA is shown in Table 5 [Sinyak, 1990; 1991]. All intermittent energy projections in the following are made against this scenario, i.e. the energy fractions are reported in respect to these figures.

Table 5
Global energy and electricity projections.
Enhanced energy conservation scenario [Sinyak, 1991].

	1990	2000	2010	2020	2030	2040	2050
World primary energy [btoe]	8.5	10.0	10.6	11.3	12.0	12.9	13.4
World electricity ['000 TWh]	11.0	12.5	15.0	17.5	22.0	24.5	27.0
Electricity in LDCs ['000 TWh]	1.4	2.1	3.1	4.4	6.7	8.6	10.5

4. FRAMEWORK OF ANALYSES

The scenarios of this paper are backed with a range of analyses that are split into two time ranges: up to year 2020 and the time period 2020-2050. The key question for the first phase (1990-2020) will be the industry capacity expansion; the manufacturability of new energy sources will thus determine the pace of their market introduction and eventually their role in the world energy scene. This time period may also be considered as the first, or early, phase of the diffusion process of new technologies into the market, characterized by further technology improvements and cost reductions. At the end, i.e. in year 2020 after a slow intial rate of adoption, selected new technologies would be ripe for mass production and may expand into the energy market with exponential growth rates. For a new technology to play a more significant role during the next phase of the diffusion (2020-2050), at least a 1 % fraction of the world primary energy in year 2020 is required. Material inputs or resources in general, perhaps except for capital, are not limiting factors in the first phase of introduction. Institutional barriers may be considered as the most restriciting factor.

The second phase from year 2020 to 2050 is charactarized by substitution market mechanisms and the market share is derived from a logistic growth curve. This penetration phase would continue until a certain market share (tens of per cents), i.e. up to the saturation point, whereafter the decline sets in. Saturation is not expected to occur by year 2050 for any of the new energy technologies. The expansion rate may be restricted by several infrastructural factors. Here, we have considered the following set of important limitations: renewable resource, available space, material production, capital, energy storage, and net energy.

The maximum utilization rate of a technology in respect to previously mentioned factors is searched for, or alternatively, it is checked that the factors are acceptable in a larger energy production context. The resource and infrastructural requirements of a technology must thus be well below the maximum values to have chances to be realizeable in the future. For some resources required, e.g. material components, the production volume of the resource could eventually be increased to meet a growing resource demand due to a new energy technology.

5. LONG-TERM PROJECTIONS FOR SOLAR-BASED NEW SOURCES IN A WORLD ENERGY SUPPLY

5.1 Some limitations for expansion

The renewable solar resource as such is very large: the solar radiation on earth's surface is 19,000 btoe/yr and wind energy some 250 btoe/yr [Häfele, 1981]. The possibly utilizable resource is only a minor fraction of the above figures due to the low energy density and variability of these sources. For comparison, the world primary energy demand in 1990 was 8.5 btoe/yr. Much of this resource potential, notably the sun, is available in ample in the LDCs.

Available space is one of the main physical resources needed by new energy technologies because of the low energy density of the primary energy source (sun, wind). The land requirement of a renewable energy system is on the order of 30,000 to 75,000 m^2 per MW(e) compared to 100-300 m^2 per MW(e) for fossil or nuclear technologies when only the final stage of the energy cycle is considered [IAEA, 1991]. Accounting for the total fuel cycle defined as the sequence fuel extraction, transportation, treatment, storage, utilization or conversion, and decomissioning, the land requirements of the various energy sources would be much closer to each other. Followingly for U.S. conditions, it has been estimated that the land use of coal is 3,600 m^2/GWh, wind 1,355 m^2/GWh, photovoltaics 3,200 m^2/GWh, and solar thermal power 3,600 m^2/GWh [Flavin, 1990].

House roofs and desert areas are naturally suitable for solar energy conversion devices. Of all global land some 15 %, or 22.4 million km^2, is classified as deserts [Weingart, 1979]. Winter et al (1988) have found 600,000-1,900,000 km^2 of high insolation arid areas that could be suitable for large-scale centralized production of solar energy in the form of hydrogen. In rural areas, the roofs may provide a good place for solar collectors. For industrialized countries, 20-40 m^2 per capita may be a good estimate for the total available roof space area - in Finland the value is 30 and in Germany 35 m^2 [Bloss, 1991]. Some 20% of the above values is suitable for solar purposes. This would correspond to some 7,000 km^2 of installed photovoltaic modules in industrialized countries only. For comparison, 1,000 km^2 of photovoltaic power modules produce 0.1 btoe/yr primary energy. In addition, the south facades of buildings may offer additional space for solar collectors. Clearly, available space should not be a major restriction even for large-scale solar energy utilization.

In case of wind energy, preferable areas would be shore-sides, mountainous regions, or offshore areas. A previous estimate of the global available surface area for wind energy utilization has indicated a 8 btoe/yr gross potential [Häfele, 1981].

Building new energy infrastructures will require large material inputs. Tables 6a and 6b give an estimate of the demand and production of most critical materials for the basic conversion components for the considered technologies [Bailey, 1981; Grum-Schwensen, 1990; Hynes, 1991; Lund, 1983; United Nations, 1989; U.S. Department of Interior, 1990]. The total material requirement varies from 0.05 to 0.25 kg/W_p. Storage or other indirect larger infrastructure needs may increase these figures as indicated by the somewhat higher values given by [Winter, 1988].

Table 6a
Global production and energy intensities of selected materials

Material	Production [Mtons/yr]	Reserves [x prod]	Energy Intensity [kWh/kg]
Aluminium	17.3	225	73.8
Steel	778	300	15.6
Cement	1100	large	0.36
Copper	8.5	40	31.9
Glass	7.1	large	7.5
Plastic	48.9		
Semicondutors:			
Si (c-Si)	0.001		13900
Si (a-Si)	0.05	large	
In (CIS)	0.00009		
Se (CIS)	0.0015	46	
Cd (CdTe)	0.02	165	
Te (CdTe)	0.00007	50	

Table 6b
Material requirements for new energy technologies [g/W_n]

Material	Solar th pow	Photo1	Photo2	Wind	Solar heat
Aluminium	6	3	6	6	6
Steel	51	81		128	23
Cement	80	140		70	
Copper	3				7
Semicondutors:					
Si (c-Si)		3			
Si (a-Si)			0.05		
In (CIS)			0.03		
Se (CIS)			0.03		
Cd (CdTe)			0.1		
Te (CdTe)			0.1		
Glass		25	70		14
Plastic		1	1	3	
Total	140	253	77	204	53

Photo1= crystalline silicon; Photo2= thin-films (a-Si, CIS or CdTe)

All new energy sources are net energy producers. The following energy pay-back times were obtained for the basic conversion components in standard conditions: solar thermal power 0.9, thin-film photovoltaics 1.3, crystalline silicon photovoltaics 26.9, wind energy 1.7, and solar heating 1.1 years. These figures include also the energy needed for material processing, work, and transportation (25% of the material energy investment), but not possible infrastructural requirements (e.g., storage). Also, the pay-back times change with site of the intermittent energy system. In case of crystalline silicon, the net energy production is, due to the large need of energy intensive semiconductor material, very marginal. Thus, for large-scale photovoltaics utilization, only thin-film production technologies could be feasible.

The volume of material production is important for a global analysis as new technologies are inherently material intensive. It is obvious that the whole production of a certain material may not be used for new energy technologies only, but on the other hand, it is also likely that annual production of new materials could be expanded from present levels. How the material component may limit the penetration of new energy technologies in the future is a manysided question and would require a comprehensive analysis to be answered in detail and is outside the scope of the present study.

Some indication of the restrictions in respect to main bulk materials, i.e. aluminium, steel, and cement, is given by the fact that no new technology would in our scenarios need more than 10 per cent of current global production. For comparison, the automobile industries use some 5% of all world steel production for cars. Some semiconductors for photovoltaic modules may turn out to be critical. CIS or CdTe photovoltaic technologies rely on relatively rare metals, wheras amorphous silicon technology could make use of the huge silicon base in earth's crust. A large-scale solar electricity scheme could increase considerably the demand of flat glass which is the major bulk material component for thin-film photovoltaics (world production of flat-glass was 10^9 m^2 in 1987 [United Nations, 1989]). Increasing world glass production would not be a problem as the major constituents needed are sand, limestone, and soda which are available in ample. New glass production facilities may also be located closer to the solar utilization areas, e.g. in less developed countries. In any case, material production does not seem to be critical for the growth rates and market shares of new energy technology considered here.

Energy storage has been considered as one of the severest constraints for large-scale utilization of intermittent energy sources. Recent studies indicate that in well-established energy infrastructures some intermittency may be allowed as existing energy production plants are able to compensate smaller "disturbances" [Grubb, 1988]. For electricity production, this limit is here taken as 15 % of the present electricity production capacity (power). Thus, e.g. decentralized solar houses may feed their excess electricity to the grid in the summer and draw mains electricity in the winter during lower solar insolation levels. The same ratinonale applies for large centralized wind farms or solar power plants.

For larger intermittent energy fractions, the mismatch between production and consumption has to be compensated through the use of energy storage or alternatively some back-up energy system. Depending on the storage requirement, one may distinguish between short-term (maximum a couple of days) and long-term (several months) energy storage. Table 7 gives a summary of the rules and boundary conditions used to quantify the storage need. If intermittent technologies are used in parallel then the 15 % non-storage fraction refers to their total contribution. The energy storage requirement is crudely assessed by allowing first a certain fraction of the intermittent energy to be supplied directly to a typical load without storage and the exceeding amount is then subject to the storage requirement. To determine the exact storage need, detailed information of the behaviour and structure of the local energy system would be needed.

Present storage technologies available are unmature for large-scale energy storage. For storage of electricity, pumped hydro storage, or electrochemical batteries are the most readily available. The world-wide hydro storage capacity is estimated to be below 100 TWh_s (subscript s refers here to storage capacity). The annual production of lead-acid batteries in 1987 was about 0.3 TWh_s [United Nations, 1989]. Energywise these are negligible compared to possible global needs and may have an impact only regionally and for short-term storage needs in niche markets. Compressed air storage (CAES) has been successfully demonstrated for large-scale diurnal storage but its applicability for long-term storage is still uncertain. Also, CAES technology is very much dependent on the local geology. Superconducting magnetic storage systems may also increase the diurnal storage possibilities in the coming years. For small-scale and long-term energy storage, some short-term storage technologies may in general be applied but this option needs to be technically verified. For large-scale seasonal storage needs in the future, hydrogen provides through its high energy storage density an interesting but still an unmature solution. Hydrogen could be produced electrolytically by new energy sources and stored or transported for later use. Hydrogen would be most suitable for large-scale solar energy utilization in deserts [Häfele, 1981; Winter, 1988].

Where direct energy storage is not available or cost-effective, intermittent energy production systems could be completed with back-up or stand-by power systems. This is often the case with present applications, e.g. remote or village power systems, in which the renewable energy source functions as a fuel saver and the power is provided with a diesel generator. For solar thermal power plants (SEGS), natural gas has been used as a supplemental energy source. The LUZ SEGS plants in California use some 25% natural gas to achieve a more continious operation [Kearney, 1991]. Another viable option could be the utilization of LNG and gas-turbines as stand-by power. From an economical point of view, power may be considered relatively cheap as compared to energy. However, relying just on fossil-based back-up power may not be acceptable if the market share of new energy sources is high as this would automatically imply a high share for fossil back-up energy, too.

New energy sources seem to be competitive after year 2020 provided that large storage or or other infrastructural investments are not needed. For some technologies and climatic conditions, the competitiveness could be reached much earlier. The capital needed for investments up to year 2020 from now on is estimated to be of the order of 700-800 billion US$. Taking $50/MWh as the break-even price of energy, then some 25-30 per cent of the above figures would need to come from public subsidies. Any kind of environmental fees or taxes on energy production would reduce the amount of the public support.

Table 7
Energy storage requirements

Solar thermal power

- o mainly centralized use in the sun-belt regions
- o up to 15 % of electricity capacity without storage
- o LDCs need only short-term storage
- o up to 1/3 of the electricity in industrialized countries through short-term storage
- o if solar > (LDC+grid-connected+short-term storage) then long-term storage
- o short-term storage requirement is 6 Wh/W_n
- o long-term storage requirement is 100 Wh/W_n (monthly storage)

Photovoltaics

- o centralized and decentralized use in all climate zones
- o grid-connected PV up to 15 % of electricity capacity in industrialized countries
- o LDCs need only short-term storage (sun-belt regions)
- o up to 1/3 of the electricity in industrialized countries through short-term storage
- o if PV > (LDC+grid-connected+short-term storage) then long-term storage
- o short-term storage requirement is 6 Wh/W_n
- o long-term storage requirement is 300 Wh/W_n (seasonal storage)

Wind power

- o grid-connected wind up to 15 % of electricity capacity in industrialized countries
- o additional 15% gained through short-term storage
- o if wind > (grid-connected+short term storage) then long-term storage
- o short-term storage requirement is 6 Wh/W_n
- o long-term storage requirement is 100 Wh/W_n (monthly storage)

Solar heating

- o all solar heat needs short-term storage 5 Wh/W_n
- o long-term storage needed if solar heat exceeds 6 % of all primary energy
- o long-term storage requirement is 200 Wh/W_n

5.2 Next 30 years: growth of industry infrastructure

The introduction of new energy technologies has already started regionally. In some areas, e.g. in California or in Denmark intermittent energy sources have a market share of a few percent of all electricity production. Looking now on the various projections shown in Chapter 2.3 it is obvious that this trend could be more of a global nature in the 1990's.

During the technology introduction phase, the market share (f) is quite low (much under a few per cent) and does not follow a typical logistic substitution model, but is characterized with much higher and also fluctuating growth rates. For example, the average annual growth rate of nuclear energy from late 1950's to the 1980's was over 20 per cent per year [Häfele, 1981]. Between 1966-1976, the increase was 31 %/yr. Nuclear energy reached a f=1% in the early 1970's, f=2-3% around 1980, and f=5.3% in 1988 [Häfele, 1981; World Resources Institute, 1990]. As the market share grows and enters the substitution phase (f is several per cents), the annual growth rate will also decrease.

We assume here that the industry manufacture growth rates of new energy technologies as predicted for the 1990's will also be valid until a few per cent world market share. This level may be reached around year 2020. The growth rates to be used have been prevailing since mid-80's.

According to our prediction in Table 8, wind power and photovoltaics are in year 2020 close to the substitution limit. Solar thermal power and solar heating may have regional significance but would contribute much less than the two previous technologies. Solar thermal power would mainly be utilized in the sun-belt regions of the U.S. and in some other desert areas. Solar heat may be used more widely for e.g. water heating but its share would not be significant in 2020.

As most of the development work and utilization of intermittent technologies have so far taken place in the U.S., it is of interest to compare the energy projections in Table 8 with those made for the U.S. alone. In Table 9 [SERI, 1990], a summary analysis is given of the U.S. situation in year 2020 and 2030 along with the world situation in year 2020 from Table 8. The lower values correpond to a business-as-usual case and the upper ones to intensified R&D. As the the share of the North America of world primary energy in 2020 is some 20 per cent [Sinyak, 1990], the projections in Table 8 for the whole world in the light of the U.S. projections can be considered realistic. Today some 75 per cent of all intermittent energy is produced in the U.S.. Taking the interval shown in Table 9, this share would be between 30-80 per cent in year 2020.

Summarizing, a central question for the development of the new energy technologies during the next 20-30 years will be the expansion of the existing niche markets into larger early utility applications that in turn would increase the industry manufacture capacity and reduce the production costs.

Table 8
Reference projections for new energy technologies 2000-2020

	2000	2010	2020
PHOTOVOLTAICS			
Average industry growth rate, %/yr	26	26	25
Average annual growth rate, %/yr	23.6	24.6	25.1
Installed capacity, TW_n	0.003	0.03	0.21
Share of world electricity, %	0.04	0.26	2.11
Share of world primary, %	0.01	0.11	0.99
WIND POWER			
Averge industry growth rate, %/yr	26	15	15
Average annual growth rate, %/yr	22.5	16.9	14.6
Installed capacity, TW_n	0.015	0.07	0.30
Share of world electricity, %	0.24	0.97	3.20
Share of world primary, %	0.09	0.42	1.5
SOLAR THERMAL POWER			
Average industry growth rate, %/yr	23	20	15
Average annual growth rate, %/yr	25.2	19.8	16.3
Installed capacity, TW_n	0.003	0.02	0.09
Share of world electricity, %	0.05	0.27	1.04
Share of world primary, %	0.02	0.12	0.50
SOLAR HEATING			
Average industry growth rate, %/yr	6	10	10
Average annual growth rate, %/yr	6.8	4.8	5.8
Installed capacity, TW_n	0.03	0.05	0.08
Share of world heat, %	0.14	0.21	0.36
Share of world primary, %	0.03	0.05	0.09

Table 9
Projections of utilization of new energy sources in the United States as the share (%) of world primary energy in 2020 and 2030

	2020 U.S.A.	2030 U.S.A.	2020 World
Photovoltaics	0.2-0.5	0.7-1.5	1.0
Wind power	0.5-1.5	0.7-2.3	1.5
Solar thermal power	0.3-0.8	0.7-2.0	0.5
Solar heating	0.1-0.2	0.2-0.3	0.1

5.3 Beyond year 2020: main penetration into energy markets

The penetration of new energy technologies is assumed to be governed by a logistic substitution model when they reach a few per cent of the world market share. An energy source may, as in case of natural gas and oil [Häfele, 1981], stay for a decade at the few per cent level before energy substitution takes off, but we assume here that new technologies progress directly to a substitution phase. The logistic model has well described the evolution of global energy markets in the past and has often been used for energy projections. The resource requirements will now be much higher and the lead times for changes due to the inertia of the energy infrastructures may be considerable. These all factors put limitations to the market growth rate of a technology.

The general logistic energy substitution model is described by the equation [Häfele, 1981]

$$f' = \alpha\, f(1-f),$$

where f(t)=share of the global market, α=annual growth rate of the market share. Solving for f, gives through integration

$$f(t) = [1+e^{-\alpha t+\beta}]^{-1},$$

where β= integration constant. From a historical perspective, the annual growth rate of oil and natural gas has been 4.8-4.9 %/yr. In case of nuclear energy, the penetration rate often assumed is at the upper end of penetration rates for other forms of energy experienced so far. This value is e.g. by Häfele (1981) 6.3%/yr which we also take as a reference value for the new energy technologies. Regionally, even higher penetration rates have been witnessed, e.g. 10%/yr for oil in the OECD primary energy supply. Besides the reference case, a low (minimum α=5%/yr) and high (maximum α=8%/yr) growth scenario is presented.

Technology characteristics and the outcome of the analyses in the preceeding chapters indicate that wind power and photovoltaics would be the most promising intermittent technologies for a global energy supply. Solar power and heat may produce cheap energy, but their impact would be more of regional than global nature. We therefore assume that only wind power and photovoltaics would in year 2020 start to enter a logistic growth pattern and that the two other technologies would still remain at the technology introduction level.

The reference scenarios for wind and photovoltaics along with solar power and heat are shown in Table 10. The projection ends up with a 19 per cent contribution from all intermittent energy sources in year 2050. No major resource limitations are imposed on the market shares and manufacture capacities shown except to world glass manufacture capacity that would need to double to satisfy the needs of photovoltaic technology in year 2050.

New energy technologies will increase the need of energy storage and/or of rapid back-up power such as gas turbines. The assessment of the storage requirement is in the end an optimization problem in which the whole energy system needs to be considered. For instance, if much peak-power were locally available the compensation possibilities are much better than for a base-power intensive infrastructure. In our case, such a detailed analysis was not possible and the storage requirement was determined outgoing from the information given in Table 7.

If wind power and photovoltaics are utilized geographically far apart, e.g. in different world regions, large short-term energy storage facilities would be needed from year 2030 onwards. (3 TWh$_e$ in 2030, 20 TWh$_e$ in 2050). For comparison, the present world battery production corresponds to some 0.3 TWh$_e$ [United Nations, 1989]. Back-up power may be the easiest technical solution to compensate for the short-term variations in this case. Long-term storage is needed just for wind energy (30 TWh$_e$ in 2040 and 120 TWh$_e$ in 2050) which could still be handled by back-up power systems, e.g. LNG.

If solar and wind were used simultaneously in parallel, the storage requirement grows due to the increased intermittence of electricity production. Large-scale long-term energy storage is necessary from year 2040 onwards ranging from 100 to 300 TWh$_e$ in year 2040 to 300-1600 TWh$_e$ in year 2050 depending on the mutual fractions of solar and wind. The upper values represent the worst case.

The sensitivity of the market shares to the growth rate is demonstrated in Table 11. A major limitation for the high growth rate (8%) scenario is energy storage and a widely available solution for seasonal storage would be a necessity already in year 2040. With a growth rate comparable to oil or natural gas (5%), the total market share of photovoltaics and wind in year 2050 is over 10 per cent with only minor storage requirements for wind energy beyond 2040 (in 2050 10 TWh$_e$ short-term and 50 TWh$_e$ long-term).

Energy storage may thus turn out to be a key problem on a long run for the penetration of new energy sources as in year 2050 over 30% (worst case) of all intermittent energy may need to be stored over long time periods, or alternatively, fossil fuels may be needed in large quantities to provide back-up. Making new energy sources into storeable and tradeble fuels, e.g. through solar hydrogen production in deserts or off-shore wind hydrogen production, may be an interesting option to consider for next mid-century.

The overall costs of implementing the reference scenario (1990-2050) is 6475 billion US$ (the share of photovoltaics is 0.40, wind 0.37, solar thermal 0.18, and solar heating 0.05 of the total global investments). The additional costs from infrastructure requirements are excluded. The storage requirement may increase the investments by 130 to 1300 billion US$. For comparison, to realize the enhanced energy conservation scenario in Table 5 including new energy sources, Sinyak (1991) has estimated a total investment need of 94308 billion US$ of which 60818 billion US$ for production and conversion. Our scenario corresponds to about 13 per cent of the above figures which is somewhat smaller than the projected share of new energy sources of all energy (19 per cent in 2050). The difference may be explained by additional infrastructural needs omitted in our analyses but also by the fact that the new energy sources increase their share mainly after year 2020 and thus cause minor investment needs prior to that.

Table 10
Long-term projections for new energy sources. Reference case.

	2020	2030	2040	2050
PHOTOVOLTAICS				
Share of world energy, %	1.0	1.8	3.4	6.2
Share of world electricity, %	2.1	3.8	5.6	9.8
Installed capacity, TW_n	0.2	0.5	0.8	1.5
Manufacture capacity, TW_n/yr	0.05	0.06	0.1	0.2
Growth of market share, %/yr	25	8	6	7
WIND POWER				
Share of world energy, %	1.5	2.8	5.2	9.3
Share of world electricity, %	3.2	5.0	8.5	14.2
Installed capacity, TW_n	0.3	0.6	1.0	1.9
Manufacture capacity, TW_n/yr	0.05	0.06	0.17	0.27
Growth of market share, %/yr	15	7	7	6
SOLAR HEAT				
Share of world energy, %	0.1	0.2	0.3	0.7
Share of world heat, %	0.4	0.7	1.4	3.1
Installed capacity, TW_n	0.08	0.2	0.4	0.8
Manufacture capacity, TW_n/yr	0.01	0.03	0.06	0.1
Growth of market share, %/yr	6	7	7	7
SOLAR POWER				
Share of world energy, %	0.5	1.2	2.0	2.9
Share of world electricity, %	1.0	2.2	3.5	4.8
Installed capacity, TW_n	0.1	0.3	0.4	0.7
Manufacture capacity, TW_n/yr	0.02	0.03	0.06	0.09
Growth of market share, %/yr	16	10	6	4

Table 11
Range of long-term projections for photovoltaic and wind energy utilization as share (%) of world primary energy.

	2020	2030	2040	2050
PHOTOVOLTAICS				
min (α=5%/yr)	1.0	1.6	2.6	4.3
reference (α=6.3%/yr)	1.0	1.8	3.4	6.2
max (α=8%/yr)	1.0	2.2	4.7	9.9
WIND POWER				
min	1.5	2.5	4.0	6.5
reference	1.5	2.8	5.2	9.3
max	2.1	3.3	7.1	14.5

6. DISCUSSION OF RESULTS

The total contribution of new energy sources in world primary energy and electricity production from 1990 to 2050 as projected in this paper is summarized in Figure 1 (reference case). The market share of world primary energy in year 2030 would be 6%. By year 2050, this share has grown up to 19%, or to an equivalent of 2.6 btoe.

The infrastructural possibilities for such a growth are positive. Global material inputs and industry manufacture capabilities seem to be adequate to support the realization of the scenario. By year 2030, large-scale energy storage will be of minor concern, but in the year 2050 working solutions have to be available. On a long-term run, the storage question may turn out to be the most limiting factor for the utilization of new energy sources. The importance of the problem would justify further analyses to quantify its magnitude more accurately. Hydrogen may offer an interesting future option in this respect due to its fuel-like characteristics although the efforts needed to realize such an infrastructure are huge. As to costs, new energy sources are predicted to be competitive after year 2020 if no larger infrastructural changes are needed. New energy sources would benefit of introducing societal costs into the energy production.

Our renewable projections are consistent to other earlier scenario results. For example, a comprehensive IIASA work predicts a 7% share in 2030 and 22% in 2050 for new technologies [Häfele, 1981]. The U.S.EPA climate stabilization study gives a 9-15% share to solar sources of electricity of primary energy in year 2050 [Lashof, 1989]. A more detailed summary of other global scenarios has been reported by Sinyak (1990).

The commercial introduction of solar and wind energy during the next 20-30 years to increase their total world energy market share from the present 0.03-0.04 per cent to a few per cent will be vital for the long-term perspectives of new energy technologies. To reach a few per cent level, the industrial manufacture capacity needs to be increased by 15-25 per cent per year. These figures are high but may be met during the 1990's based on existing national programmes. Projections for the United States alone indicate that this trend may have chances to last long enough that a penetration level could be reached around year 2020 [SERI, 1990].

Taking the year 1990 world primary energy mix as a basis, the savings in carbon dioxide emissions in year 2050 in our reference scenario are about 2 GtC/yr. The IPCC projects for year 2050 some 15 GtC/yr CO_2 emissions from the global energy system for a business-as-usual-case and a halving of that by shifting to low-carbon fuels and energy efficiency. In respect to these figures, the intermittent energy sources may be viewed as an important but not the exclusive measure for mitigating global environmental problems.

ACKNOWLEDGEMENTS

An important part of the analyses were made during the author's visit to the International Institute of Applied System Analyses (IIASA) in Laxenburg, Austria in October 1991. The author wishes to thank Professor Yuri Sinyak from IIASA for his help and valuable comments and views on the paper.

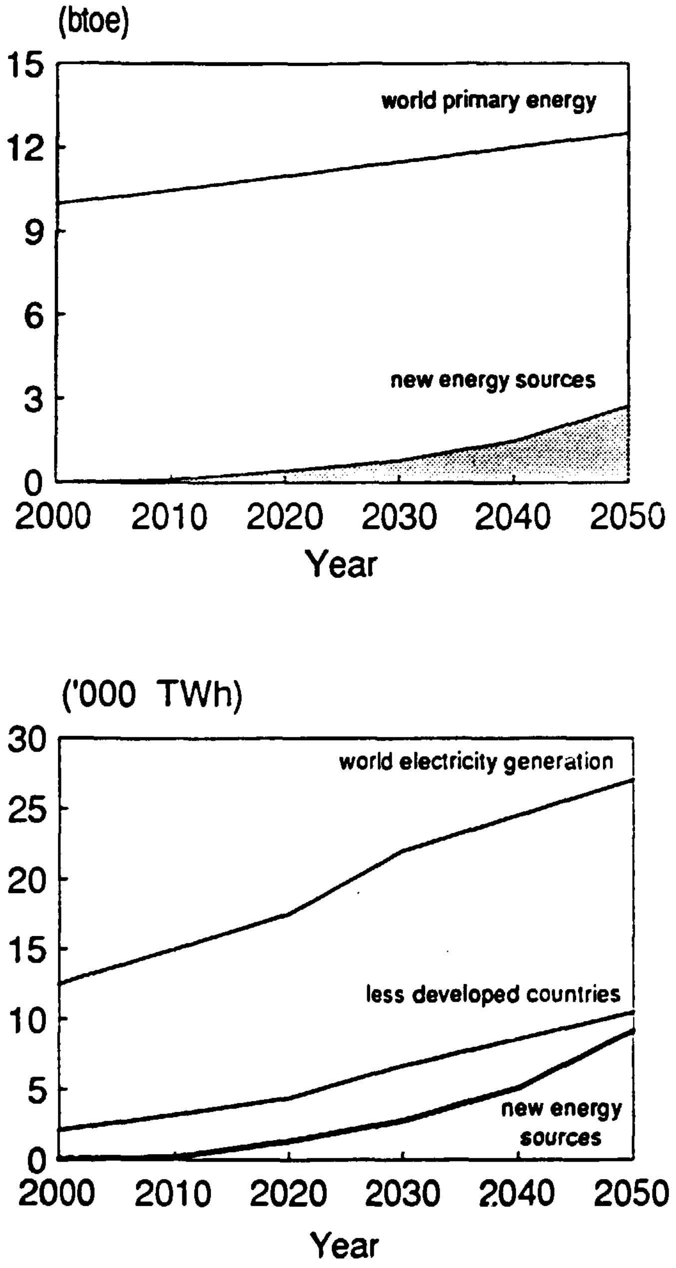

Figure 1. Long-term projections for intermittent energy sources.
Reference case.

REFERENCES

Annan, R. H., et.al., Integration of Photovoltaics into Electric Utilities:Issues and Approaches. In Proc. of the 10th CEC Photovoltaic Solar Energy Conference, Lisbon, Portugal, 8-12 April 1991, 734-738.

Bailey, R.A., Net Energy Analysis of Eight Technologies to Provide Domestic Hot Water Heat. Energy J., Vo. 6, 983-997 (1981).

Bloss, W.H., Grid-Connected Solar Houses. In Proc. of the 10th CEC Photovoltaic Solar Energy Conference, Lisbon, Portugal, 8-12 April 1991, 1295-1300.

Blum, S. and Barber, J. (Eds), National Solar Heating and Cooling Programs in IEA Countries 1988. IEA Solar Heating and Cooling Programme, U.S.A., 1989.

Clarke, A., Wind Energy: Progress and Potential. Energy Policy, Vol. 19, 742-755(1991)

Electric Power Research Institute, Emerging Strategies for Energy Storage. EPRI Journal, Palo Alto, July/August 1989.

Electric Power Research Institute, Renewables on the Rise. EPRI Journal, Palo Alto, June 1991.

European Wind Energy Association, Wind Energy in Europe. Italy, October 1991.

Flavin, C. and Lenssen, N., Beyond the Petroleum Age: Designing a Solar Economy. Worldwatch Paper 100, December 1990.

Flavin, C., et. al., Sustainable Energy. Renew America, Washington, 1989.

Grubb, M., Ph.D. Thesis, Imperial College, London, 1988.

Grum-Schwensen, E., The Real Cost of Wind Turbine Construction. Wind Stats Newsletter, Vol.3, 1-2(1990).

Häfele, W., Energy in a Finite World. Ballinger Publishing Company, U.S.A., 1981

Hynes, K.M., et.al., Sensitivity Analysis of Energy Requirements for Thin Film Photovoltaic Module Production. In Proc. of the 10th CEC Photovoltaic Solar Energy Conference, Lisbon, Portugal, 8-12 April 1991, 461-464.

Iannucci, J.J. and Weinberg, C.J., A Diffusion Model for the Entry of Photovoltaics into Utilities. Pacific Gas and Electric Company, Report 007.3-91.4, California, May 1991.

International Atomic Energy Agency, Senior Expert Symposium on Electricity and the Environment. Key Issues Papers. Helsinki, 13-17 May 1991.

Intergovernmental Panel on Climate Change, IPCC First Assessment Report, Vol 1.. August 1990.

International Energy Agency, Energy Policies and Programmes of IEA Countries. 1989 Review. OECD, Paris, 1990.

Johansson, T.B., et.al, Electricity. Efficient End-Use and New Generation Technologies, and Their Planning Implications. Lund University Press, 1989.

Kearney, D., et.al., Status of the SEGS Plants. Proc. of the Biennial Congress of the International Solar Energy Society, Denver, Colorado, U.S., 19-23 August 1991, 545-551.

Lashof, D.A. and Tirpak, D.A., Policy Options for Stabilizing Global Climate. Executive Summary. United States Environmental Protection Agency. February 1989.

Levine, M.D., et.al., Energy Efficiency, Developing Nations, and Eastern Europe. A Report to the U.S. Working Group on Global Energy Efficiency. U.S.A., June 1991.

Lund, P.D., Implications of a 1% World Primary Energy Share on Solar Photovoltaics in 2020. Helsinki University of Technology, Report TKK-F-A665 (1990).

Lund, P.D. and Kangas, M.T., Net Energy Analysis of District Solar Heating with Seasonal Heat Storage. Energy Journal, Vol. 8, 813-819 (1983).

Musgrove, P.J., Energy Analysis of Wave-Power and Wind-Power Systems. Nature Vol. 262, 206 (1976).

Ogden, J.M. and Williams, R.H., Solar Hydrogen. Moving beyond Fossil Fuels. World Resources Institute, Washington D.C., October 1989.

Organisation for Economic Co-Operation and Development, Energy Technologies for Reducing Emissions of Greenhouse Gases. Proc. of an Experts' Seminar, Paris, 12-14th April 1989. OECD, Paris, 1989.

Schleisner, L. et. al., Hydrogen as an Energy Carrier. Risö National Laboratory, Report Risö-M-2940 (June 1991).

Sinyak, Y., Global Energy/CO_2 Projections. International Institute for Applied System Analysis, Austria. Working Paper WP-90-51, September 1990.

Sinyak, Y. Private Communication (October 1991).

Smith-Morris, M. (Ed.), Vital World Statistics. The Economist Books, U.K., 1990.

Solar Energy Research Institute, The Potential of Renewable Energy. An Interlaboratory White Paper. Solar Energy Research Institute, Report SERI/TP-260-3674, March 1990.

United Nations, Industrial Statistics Yearbook 1987, Vol. I and II. New York, 1989.

United Nations, 1988 International Trade Statistics Yearbook, Vol. 2. New York, 1990.

United Nations, Statistical Yearbook 1987. New York, 1989.

U.S. Department of the Interior, Minerals Handbook 1988. Washington, 1990.

Weinberg, C.J. and Williams, R.H., Energy from the Sun. Scientific American, Vol.263, 98-108(1990).

Weingart, J.M., Global Aspects of Sunlight as a Major Energy Source. Energy Journal, Vol.4, 775-798(1979).

Winter, C.-J. and Nitsch, J. (Eds), Hydrogen as an Energy Carrier. Spinger-Verlag, 1988.

World Energy Conference, 14th Congress, Paris (1989).

World Resources Institute, World Resources 1990-91. Oxford University Press, Oxford, 1990.