Distr.
GENERAL
E/ESCWA/ENR/2001/4
20 November 2001
ORIGINAL: ENGLISH

ECONOMIC AND SOCIAL COMMISSION FOR WESTERN ASIA

POTENTIAL AND PROSPECTS FOR RENEWABLE ENERGY ELECTRICITY GENERATION

VOLUME I

OVERVIEW OF WIND AND BIOMASS SYSTEMS

United Nations
New York, 2001

01-0986

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ABBREVIATIONS

£	pound sterling
AC	alternate current
AGFUND	Arab Gulf Programme for United Nations Development Organizations
ARC	Agricultural Research Center
ASRT	Academy of Scientific Research and Technology
AWEA	American Wind Energy Association
BIG/GT	Biomass-gasifier gas turbines
BOD	Biological Oxygen Demand
BOOT	build-own-operate-transfer
BREEPP	Bulk Renewable Energy Electricity Production Projects
C:N	carbon to nitrogen ratio
CDM	clean development mechanism
cent/kwh	cent per kilowatt hour
CH_4	Methane
CHP	Combined heat and power
CO_2	carbon dioxide
COD	Chemical Oxygen Demand
CPmax	Maximum power coefficient
DANIDA	Danish International Development Agency
DC	direct current
DESA	Department of Economic and Social Affairs (United Nations)
DKr	Danish Krona
ECU 900/kw	900 European currency per kilowatt
EEAA	Egyptian Environmental Affairs Agency
EERC	Energy and Electricity Research Council
EIS	Energy Issues Section
EJ	extra joule = 10 joule
ENRED	Energy, Natural Resources and Environment Division
EREDO	Egyptian Renewable Energy Development Organization
ESCWA	Economic and Social Commission for Western Asia
ESCWA	Economic and Social Commission for Western Asia
FAO	Food and Agriculture Organization of the United Nations
FRP	fibreglass and reinforced plastic
GEF	Global Environment Facility
GHG	greenhouse gas
GJ	giga Joule (10^9 Joule)
GW	Gegawatt
GWh/year	gegawatt hour per year
HRT	High Residence Time
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
JD	Jordanian dinar
JEA	Jordanian Electricity Authority
km^2	square kilometres
kW	Kilowatt
kWh	kilowatt hour
kWp	kilowatt peak
LFG	landfill gas
m/s	metres per second
m^3	cubic metres
MJ/Nm3	megajoule per cubic normal meter
MSW	municipal solid waste
MW	megawatt
MWe/km^2	megawatt electric per square kilometer

ABBREVIATIONS (*continued*)

MWh/MWe	megawatt hours per megawatt electric
NG	natural gas
NGO	non-governmental organization
Nm^3	cubic normal metre
NO_x	nitrogen oxides
NRC	National Research Centre
NREA	New and Renewable Energy Authority
O&M	operation and maintenance
OECD	Organization for Economic Cooperation and Development
pH	hydrogen ion concentration
PPAS	power purchase agreements
PV	Photovoltaic
R&D	research and development
RE	renewable energy
REPM	Renewable Energy Promotion Mechanism
RES	renewable energy sources
RSS	Royal Scientific Society
SO_2	sulphur dioxide
SRT	Short Residence Time
TOE/y	tons of oil equivalent per year
TW	Terawatt
TWe	terawatt electric
TWh/Twe	terawatt hour per terawatt electric
TWh/y	terawatt hour per year
UNDP	United Nations Development Programme
UNIDO	United Nations Industrial Development Organization
UNIFEM	United Nations Development Fund for Women
USAID	United States Agency for International Development
USD/kW	United States Dollar per kilowatt
V^3	cubic wind speed
W/m^2	watt per square metre
WAsP	Wind Atlas Analysis and Application Program
WEC	World Energy Council
WETC	Wind Energy Technology Center

EXECUTIVE SUMMARY

The potential and prospects for electricity generation from wind and biomass resources in the Economic and Social Commission for Western Asia (ESCWA) member countries were reviewed and analysed in this report. Particular emphasis is given to state-of-the-art technologies, current development status in the region and possible future prospects in each case.

A. WIND ENERGY ELECTRICITY

1. *Wind electricity, resource potential, sites and technologies*

(a) *Resource potential*

The economics of wind power depend strongly upon wind speed. The actual energy contained in the wind varies with the wind speed to the third power. The starting point for any wind development, then, must be a windy site but other factors come into play as well. Wind speed varies with height, which makes higher sites more attractive from a resource point of view. Wind speeds tend to be higher at sea, which may encourage the development of offshore sites; once a potential site has been identified, it must be studied to confirm that it is suitable. Long- and short-term wind speed measurements will normally be needed to ascertain the wind regime. Only when these figures are available can the economics of the project be determined with any accuracy. In general, studies proved that:

(i) The potential of wind energy is large, with the technical potential of generating electricity onshore estimated at 20,000-50,000 terawatt hours per year (TWh/y);

(ii) When investigating potential sites, special attention should go to possibilities offshore. Studies for Europe indicate that the offshore wind resources that can be tapped into are bigger than the total electricity demand in Europe.

(b) *Wind technologies development*

(i) As a result of intensive basic and applied researches over the last 20 years, development and demonstration efforts are exceptional in several industrialized countries, with leading research centres and industries in Denmark, the Netherlands, the United States of America, Germany and others. The technologies of wind turbines for electricity generation are now in full progress, particularly with respect to turbine sizes, based on the development achieved during the last two decades. During the 1980s, the standard turbine size tended to be between 300 kilowatt (kW) and 500 kW, while during the 1990s, turbine unit size continued to increase steadily. By 1998, most new wind farms employed turbines with capacities of between 600 kW and 750 kW;

(ii) Wind turbines are classified according to different criteria that affect its performance; the main classifications are according to (1) horizontal or vertical axis, (2) power control system, (3) the type of tower, and (4) wind turbine generators;

(iii) The wind farm concept was developed, which resulted in the promotion of the use of wind electricity generation to large-scale grid-connected applications. However, the maximum wind power that can be connected to a specific grid depends on the grid capacity and the permissible wind penetration rate (usually between 10-15 per cent of the grid capacity). Such wind energy is what the national transmission systems can accept while still operating reliably.

2. *Wind electricity, installed capacity development, prospects and system aspects*

(a) *Operating wind power capacity*

Wind power has enjoyed fast-paced development in recent years, mostly in the industrialized world, with Germany, the United States, Spain and Denmark emerging as the fastest growing wind markets worldwide in 1999. In April 1999, the American Wind Energy Association (AWEA) and the European Wind

Energy Association jointly announced that the world's total installed wind capacity had exceeded 10,000 megawatts (MW). In addition, more than 3,600 MW of newly installed electricity-generating capacity in 1999 brought the world total to around 13,400 MW. Such an increase is the largest addition to global wind capacity ever in a single year, with a 36 per cent increase from 1998. Germany, the United States and Spain alone accounted for more than 40 per cent of the total increase in capacity.

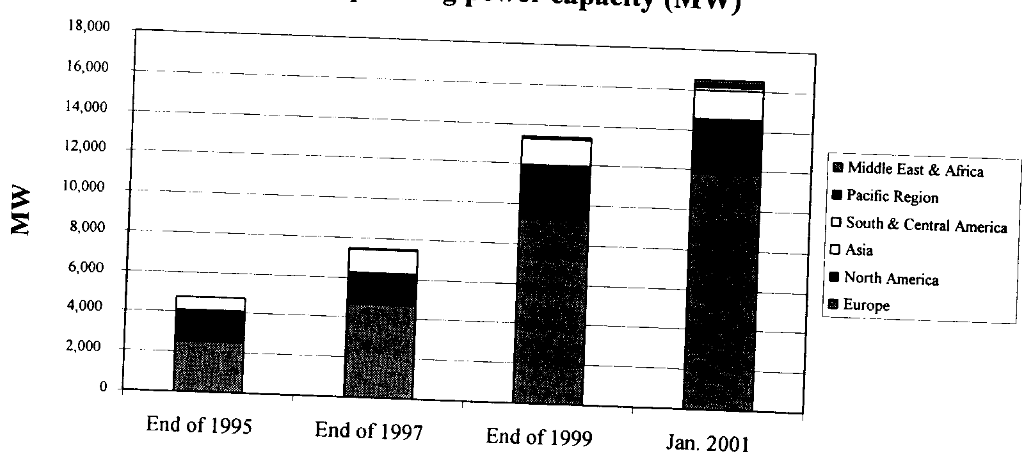
Table 2 and figure III (taken from the main report) below highlight the development of the operating wind power capacity between 1995 and January 2001.

TABLE 2. OPERATING WIND POWER CAPACITY BY REGION
(*Megawatts*)

	End of 1995	End of 1997	End of 1999	January 2001
Total Europe	2 518	4 677	9 307	11 831
Middle East and Africa				
Egypt	5	5	15	65
Morocco	0	0	0	54
Others	7	19	24	24
Total Middle East and Africa	12	24	39	143
Total Pacific Region	17	33	116	219
Total Asia	609	1 116	1 287	1 466
Total North America	1 612	1 607	2 619	2 708
Total South and Central America	11	38	87	94
World Total	4 779	7 495	13 455	16 461

Source: Windpower Monthly News Magazine, vol. 13, No. 4, April 1997.

Figure III. Operating power capacity (MW)



(b) *Projected wind power capacities*

The following scenarios were developed by WEC and others for estimating the projected wind power capacities:

(i) The recent trends scenario. Starting with 20,000 MW by the end of 2002 and assuming a 15 per cent cost reduction, and later 12 per cent, for each doubling of the accumulated number of installations, 10 per cent penetration would be achieved around 2025, and saturation would be achieved between 2030 and 2035 at about 1.1 terawatts (TW). In this scenario, the cost of generating wind electricity would come down to $0.032 per kilowatt hour (kWh) on average (1998 level), depending on wind speed, connection costs to the grid, and other considerations;

(ii) The international agreement scenario. With the same starting conditions as listed in the recent trends scenario above but with a slightly different learning curve, growth is faster and 10 per cent penetration would be achieved around 2016, with saturation being achieved between 2030 and 2035 at about 1.9 TW. In this scenario, the cost would come down to $0.027 per kWh on average.

In the second scenario, the regional distribution of wind power in North America is 23 per cent, Latin America 6 per cent, Europe (Eastern and Western) 14 per cent, Asia 23 per cent, Pacific Organization for Economic Cooperation and Development (OECD) 8 per cent, North Africa 5 per cent, former Soviet Union 16 per cent, and the rest of the world 5 per cent.

Meanwhile, the given survey of the wind resources potential, development of wind electricity technology status and aspects concludes that the average growth rate of the cumulative capacity over the last six years has been about 30 per cent per year, bringing the cumulative installed wind turbine capacity to about 10,000 MW at the end of 1998, and about 13,500 MW at the end of 1999 with a wind energy production of 18 TW hours in 1998 and 24 TW hours in 1999.

(c) *Technology developments*

The main technology development features expected in the coming decade based on the achieved development trends since the 1970s are:

(i) Wind turbines will become larger market demands, which will drive the trend towards larger machines. Economies of scale, less visual impact on the landscape per unit of installed power, and expectations that offshore potentials will soon be developed are also expected. The average size of wind turbines installed is expected to be 1,200 kW before 2005 and 1,500 kW thereafter. Note, however, that the optimum size of a turbine—including cost, impact and public acceptance—differs for onshore (nearby as well as remote) and offshore applications;

(ii) Wind turbines will become more controllable and grid-compatible;

(iii) Wind turbines will have fewer components, far lower costs and greater reliability and maintainability. Designers now seek technology with fewer components, such as directly driven, slow-running generators with passive yaw and passive blade pitch control.

Time to market is becoming shorter than project preparation time. Figure V, taken from the main report, illustrates the cost reductions for electricity generation from wind turbines in Denmark since 1981. However, it will vary for other regions based on the variables of cost of project preparation, infrastructure and civil works. Some recent Danish studies expect a 35-45 per cent reduction in generation costs in the next 15-20 years (see figure VI below taken from the main report).

Figure V. Development of wind electricity generation costs in Denmark

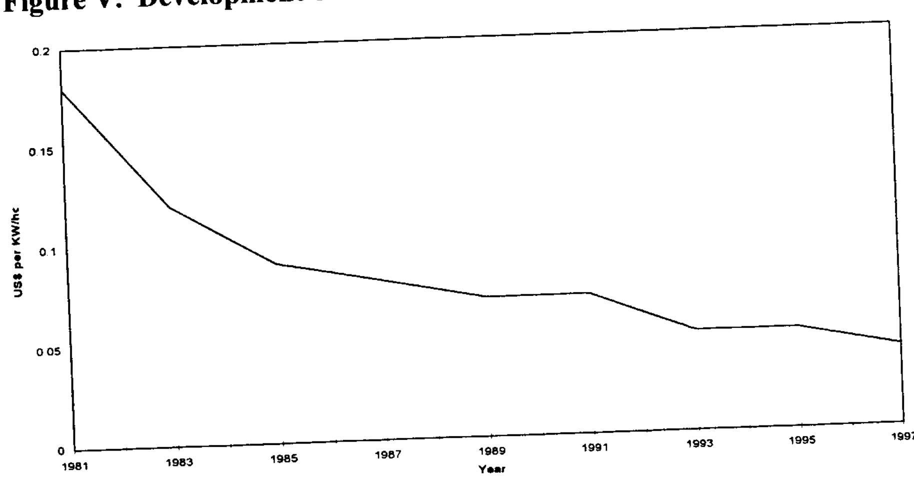
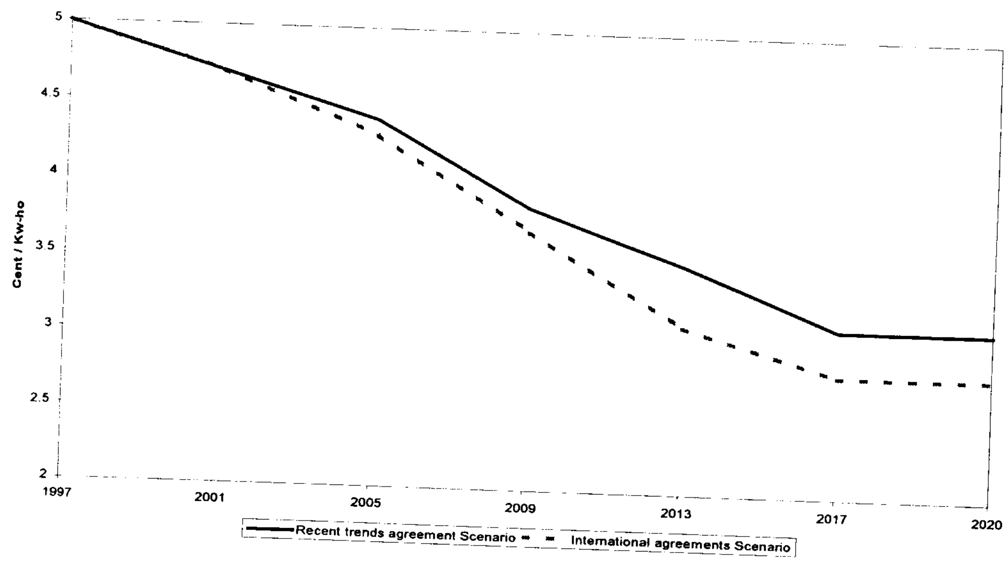


Figure VI. Potential cost reductions for wind power, 1997-2020



(d) *System aspects*

The study survey prepared indicates that future system aspects would include:

(i) Wind turbines becoming larger, with the average size installed in 1998 being 600 kW, up from about 30 kW in the mid-1970s. Megawatt-size turbines are being developed and should soon be commercially available;

(ii) Costs coming down further, requiring development of advanced flexible concepts and dedicated offs hore wind energy systems. Cost reductions up to 45 per cent are feasible within 15 years. Ultimately, wind electricity costs might come down to about $0.03 per kWh;

(iii) Transforming wind-generated electricity to a base load, even though it is normally an intermittent resource;

(iv) Awareness of the environmental impact of wind turbines, with noise and visibility causing the most problems, which in turn increases public resistance against the installation of new turbines in densely populated countries.

3. *Potentials of wind electricity in the ESCWA region*

(a) *Wind resources status*

Wind resource measurements are regularly taken by most of the meteorological organizations in the ESCWA member countries. However, they are not as precise as to satisfy the requirements for wind statistics for energy assessment. Accurate estimates of expected annual wind energy production from wind farms are necessary to facilitate the comparison of different alternative electricity generation options needed for investment decisions, as well as for site selection and design of wind farms.

The data obtained from the national weather stations could be used to determine the overview of the wind energy potential in the ESCWA member countries (course wind assessment). In order to establish a wind energy programme, a wind resource assessment programme should be adopted by each ESCWA member country in order to provide high-quality and accurate wind data.

In conclusion, it is clear from the preliminary data that the available wind data shown in table 5 below (taken from the main report) are not sufficient to accurately evaluate wind electricity potentials in almost all the ESCWA member countries; however, based on such data, wind electricity potential for ESCWA member countries can be classified into three groups:

(i) ESCWA member countries with limited or no potential for wind electricity generation: Lebanon, Palestine, Saudi Arabia and the United Arab Emirates;

(ii) ESCWA member countries with moderate potential for wind electricity generation: Bahrain, Kuwait, Oman, Qatar and Yemen;

(iii) ESCWA member countries with promising potential for wind electricity generation: Egypt, Jordan and the Syrian Arab Republic (Golan Heights).

TABLE 5. RANGE OF ANNUAL WIND SPEED AT WINDY SITES IN ESCWA MEMBER COUNTRIES

Country	Wind speed m/s
Bahrain	5-6
Egypt	4-10
Iraq	n.a.
Jordan	5.5-7.5
Kuwait	5-6.5
Lebanon	3-5
Oman	4-6
Palestine	3-5
Qatar	5-7
Saudi Arabia	2.5 – 4.5
Syrian Arab Republic	4.5-11
United Arab Emirates	3.5-4.5
Yemen	4-6.6

It should be noted that appropriate and accurate assessments may identify a specific site that could be classified in a different group than shown above.

(b) *Criteria for evaluating wind electricity potentials*

The potential for wind energy utilization for electricity generation depends on several factors but with a basic need for good wind resource sites. The following set criteria for evaluation of such potential in a specific ESCWA member country includes: (1) the available wind resources, (2) energy strategies and policies, (3) the possible wind penetration, (4) prospective site conditions, (5) available local capabilities, and (6) financial availability.

(c) *Current development status*

During the last two decades, several research institutions in the ESCWA region have carried out research and development (R&D) and demonstration projects for wind electricity generation. The wind electric systems have been demonstrated, tested and evaluated in Egypt, Jordan, the Syrian Arab Republic and Yemen. The following is a brief on the status of development in these ESCWA member countries:

Egypt has achieved remarkable success in developing the utilization of its high wind resources and has crossed the phase of demonstration to large-scale field application. The Egyptian wind energy programme for electricity generation represents a leading example in the region; by March 2001, the total wind capacity in operation reached more than 70.0 MW (63.0 MW at Zafarana, 5.0 MW at Hurghada, and 2.0 MW from other sites), partially based on locally manufactured equipment.

Jordan's wind-powered electricity generation systems were demonstrated by the Royal Scientific Society (RSS) and the Ministry of Energy and Mineral Resources at al-Ibrahimia and Hofa, in addition to a set of electric wind-pumping and battery-charging systems totalling less than 2 MW installed capacity.

The Syrian Arab Republic has only two systems totalling 150 kW where wind turbines were installed and tested.

In Yemen, a pilot experiment consisting of an 18 kW wind-conversion system was installed in 1979; eventually the system faced difficulties and was disassembled.

(d) *Prospects for wind electricity development in the region*

With the exceptions of Egypt, Jordan and the Syrian Golan Heights, the preliminary resources data do not show promising potentials for wind electricity generation in most of the ESCWA member countries. This emphasizes the need for conducting appropriate and accurate assessments for evaluating practical wind energy potential. However, the following highlights the current Egyptian potential and plans, as well as the estimated potential in Jordan and the Syrian Arab Republic:

In Egypt, theoretical potentials for wind electricity in the Gulf of Suez were estimated to be 20,000 MW, while the official development programme total by the year 2010, as indicated in chapter VI of this report, is only 600 MW.

In Jordan, the Jordanian Energy Resources Center has estimated the potential for wind resources to be more than 1,000 MW.

In the Syrian Arab Republic—apart from the "6X600 kW" wind farm installed in the Golan Heights—any further evaluation of the wind electricity generation potentials should be based on appropriate resource assessments, which are not currently available.

4. *The Egyptian experience*

Chapter IV of this report gives an overview of the Egyptian experience and concludes that the lessons learned are:

(a) The gradual identification of potential areas within the country and then concentrating on the most promising site among them for accurate resource assessment;

(b) Once the area has been identified, resource assessment should include all parameters, taking into consideration effective issues and the specification and accuracy of equipment needed as described in annex I of this report.

B. BIOMASS ELECTRICITY GENERATION

1. *Biomass resources and technologies*

(a) *Classification of biomass resources*

Biomass resources can be classified into two main groups:

(i) Primary biomass resources, which are crops specifically planted for energy production through combustion, gasification or fermentation processes. Energy crops can be produced in two ways: (1) by devoting an area exclusively to its production, which may intensify competition with other land uses; or (2) by co-mingling the production of energy and non-energy crops for increasing the economic utilization of the land;

(ii) Secondary biomass resources, which are produced as a by-product of plantation residues, animal waste, sewage and municipal solid waste (MSW). Global production of biomass residues exceeds 110 EJ (extra joule=10 joule) per year, perhaps 10.0 per cent of it is used for energy production.

If biomass is to make a major contribution to electricity generation, then crops will need to be grown specifically for energy production, and greater emphasis should be directed to effective waste collection and disposal techniques that could easily involve waste combustion.

(b) *Biomass technologies for electricity generation*

(i) *The technology*

There is a variety of modernized biomass technologies that can efficiently convert biomass resources into clean, convenient gaseous and liquid energy carriers to be used for electricity production. These technologies are in a range from the conventional to the cutting edge of research. The choice of technology can drastically affect the economics of biomass electricity and limit the size of the plant producing it. Crude biomass generally has a low energy density and this favours small, dispersed plants for converting biomass into other energy carriers. Thus, a modern gigawatt (GW) capacity steam cycle electricity plant is unlikely to be fuelled by biomass since it would draw its fuel from an enormous area, incurring prohibitive transport costs.

A range of technologies for producing fuels from biomass exists and can be used for electricity generation. These are: (1) direct combustion (conventional and improved [fluidized bed]); (2) gasification; (3) anaerobic digestion; and (4) landfill gas production. Chapter V of this report gives a briefing on the concept and development status of each of these technologies.

Combustion technologies follow the simplest approach where the biological material is burnt in a conventional boiler/steam turbine plant. Conventional steam cycle plants based on long-standing boiler designs are likely to be supplanted by newer technologies such as fluidized bed combustion.

Gasification of biomass, to produce a low energy combustible gas is being extensively piloted. More advanced systems are likely to be based on gasification, the fuel product from which may be burned in a variety of systems, but with greatest efficiency in BIG/GT plants.

The anaerobic digestion of biomass to produce biogas is likely to be of increasing importance, as is landfill gas, at least in the medium term. Gaseous fuels of any of these technologies may, in future, be used to produce electricity in fuel cells, with minimal environmental impact.

In general, there is a considerable potential for the development of biomass electricity production, particularly in the context of combined heat and power (CHP). With the exception of fuel cells, most of these technologies are mature and there are many examples already in the marketplace. The viability of some of these technologies is due to subsidies and other financial incentives in the face of cheap fossil fuels.

(ii) *The cost*

Capital costs for biomass-burning power plants based on conventional steam technology tend to be higher than for coal and gas-fired plants. Taken together with the relatively high cost of the fuel, this makes biomass uneconomical as a base-load power generation technology. However, there are circumstances, for example at a sugar-processing factory or a wood yard, where the waste is free and already at the site and the economics are much more favourable.

The fuel cost is one element of the equation. Capital cost of the generating plant is another. The cost for transport of biomass fuel is so high that fuel can be carried economically only over short distances. This will generally mean that a biomass-fired power station will be relatively small, and usually under 100 MW. For plants of this size, efficiency is at best around 23 per cent and capital cost will be around $1,900/kW, according to the Oak Ridge Laboratory. At this level of investment, power could be generated for

$0.05/kWh, with fuel feedstock prices of under $1.00/GJ (giga joule [$10^9$ joule]). Where fuel is virtually free, as in the case of some agricultural wastes, the economics are attractive.

The development of integrated gasification combined-cycle technology for biomass power generation offers a more attractive scenario. Oak Ridge estimates the capital cost of such a plant to be $1,300/kW; efficiency is around 35 per cent. On this basis, power could be produced for $0.05/kWh with fuel costs up to $2.80/GJ. This would make biomass highly competitive, even with conventional coal-fired power plants.

(iii) *Environmental impacts*

The economics of using biomass for electricity generation depends critically on the circumstances under which it is being considered. But the current practice of simple economic analysis ignores the environmental factor, and this is likely to prove the key to the future of biomass power generation.

Biomass is considered to be a renewable fuel. As such, it is viewed as environmentally benign. Even so, when biomass is burnt in a power station, it produces carbon dioxide (CO_2) in exactly the same way as coal or natural gas combustion produces CO_2. The difference lies in the fact that a new batch of biofuel is then grown. As it grows, it captures CO_2 from the atmosphere and uses it to produce new plant material. In other words, biomass cycles carbon between the fuel and the atmosphere, and the net effect on the atmospheric concentration of CO_2 of burning biomass is effectively zero. For this reason, its use is considered beneficial in helping to stabilize the atmospheric concentration of CO_2. Also the use of biomass might increase steadily beyond the year 2000.

The burning of agricultural wastes has an additional benefit of removing a waste disposal problem when the ash can often be distributed on land as a fertilizer. Meanwhile, when the growth of energy crops is considered, other factors come into play. In some parts of the world, fuel crops will compete with food for agricultural land. Economics and social needs could pull in opposite directions and lead to conflict.

2. *Biomass electricity, potentials and prospects in the ESCWA region*

(a) *Biomass potentials*

The assessment of biomass utilization potentials in the region depends on several issues, particularly the availability of resource information and the application of an appropriate criteria for such assessment.

(i) Several biomass resource assessment studies for both rural and urban areas have been carried out in the ESCWA region, mainly in Egypt, Jordan, the Syrian Arab Republic, the areas under the control of the Palestinian Authority and Yemen. However, the coverage and depth of the studies are either limited or not sufficient to evaluate potential biomass applications;

(ii) The criteria for evaluating biomass electricity generation potential in a specific country or a region depends on several issues that are in many cases country-specific as well as technology-dependent. These issues include: (a) the available biomass resources; (b) national energy policy; (c) the prevailing environmental measures; (d) availability of mature technologies; and (e) the available local capacities.

(b) *Current development status in the region*

Several ESCWA member countries have directed efforts towards evaluating biomass technologies through R&D studies, demonstration and field-testing, with exceptional examples of field applications, particularly for electricity generation. However, the achievement and level of activity for electricity generation, particularly for field applications, are very limited currently, as shown below:

(i) *R&D*

Several research and feasibility studies were carried out for investigating the potential applications of biomass in the ESCWA member countries. However, only a few were suitable for electricity generation. In

Egypt, a study was conducted in 1996 to evaluate the prospects of energy generation from solid wastes under the Egyptian conditions. Several options were considered, and preliminary assessments have been carried out for four prospective systems with large capacities (about 500 to 1,000 tons of municipal solid wastes per day) for electricity generation using different technologies. In Jordan, a preliminary study was carried out by the Ministry of Energy and Mineral Resources and the Amman Municipality to determine the feasibility of using municipal solid wastes for electricity production. In addition, the Palestinian Authority carried out a study assessing the prospects for the use of different biogas technologies for electricity generation and is being conducted in cooperation with European firms as part of a project financed by the European Union.

(ii) *Demonstration and field testing*

Biomass technologies have been demonstrated and field-tested in several ESCWA member countries. In Egypt, family-sized and large-scale mechanized units have been tested as a source of energy and for waste recycling and management. The gas produced has been used for cooking, heating, refrigeration and the production of electrical power. In Jordan, a techno-economic feasibility study for 1 MW-size electric power generation from municipal solid waste has been carried out in cooperation with the United Nations Development Programme (UNDP). The project, which is located at the Amman municipal waste disposal plant, was commissioned in March 2000 and its cost is 4 million Jordanian dinars (JD). It provides energy savings equivalent to 17,000 tons of oil equivalent per year (TOE/y). In Yemen, biogas field demonstration projects have been executed by ESCWA and funded by the Arab Gulf Programme for United Nations Development Organizations (AGFUND), United Nations Development Fund for Women (UNIFEM) and the Netherlands Government Trust Fund. These projects have included three biogas demonstration plants with different designs, which were constructed in a Yemeni village. The initial success of this activity led to the construction of 22 family-size integrated biogas systems serving 32 families in Mansourat al-Habeel village in Yemen.

(iii) *Market penetration*

The market penetration of biomass technologies, specifically for electricity production, has been very limited owing to various economic, technical and social constraints that have hindered their replication/adaptation. Efforts are being made to promote biomass energy applications, and the only exception is the huge biogas plant with 22,000 cubic metres (m^3) of digester volume used for electricity production (18 MW) in el-Gabal el-Asfer sewage treatment plant for Cairo, Egypt. However, no regular local production has yet been achieved. A similar situation exists in the Syrian Arab Republic and Yemen. No standards or codes have been issued in the region for any of the biomass energy technologies, components or systems.

(c) *Future prospects*

Although the availability of different types of biomass in the ESCWA member countries is proven, appropriate assessment and classification data are not available. This fact represents quite a constraint for possible evaluation of the application potential and future prospects of technologies that are currently mature. Efforts should be directed by national authorities, ESCWA and other regional organizations to upgrade the available database as to facilitate the required actions in this regard.

C. CONCLUSIONS AND RECOMMENDATIONS

In view of the study outcome given above, it is clear that although both wind and biomass electricity generation can have promising potentials in some ESCWA member countries, its development and utilization are still facing difficulties, particularly the absence of appropriate resource assessment to enable potential evaluations with reasonable accuracy and to facilitate project designs and technology selection. Moreover, the limited consideration given to the development of two such valuable sources within the national energy plans is an added constraint to its development.

In view of the above and in line with the general conclusions and recommendations given in Chapter VII of the main report, the following core actions are recommended:

1. Countries in the region, in cooperation with ESCWA and other active regional organizations, should direct concerned efforts towards upgrading the resource databases on wind and biomass through accurate and advanced measurement and analysis techniques. The product of such assessments should be able to serve the objectives of potential assessment and project designs.

2. Wind and biomass development should be incorporated as an integral part of the national energy plans.

3. The planning processes for the development of renewable energy applications, including wind and biomass, should take into account the whole integrated spectrum of expertise and capabilities needed and consider upgrading the national contributions to it, particularly maximizing the locally produced components, the contribution of national expertise and the operation and maintenance (O&M) capabilities.

INTRODUCTION

The demand for electric energy is tremendously increasing in ESCWA member countries. Consequently, the total installed capacity has been raised from 61.0 GW in 1990 to 74.8 GW in 1999 (1). This is owing to the commitment of ESCWA member countries to achieve progressive economic and social development for their people. As a result, a need arises for increased electricity generation capacity and its associated huge investment requirement, in addition to the resultant impact on the environment, particularly by the intensive emissions of greenhouse gases.

In spite of the achieved development of generating capacities in the ESCWA member countries, there are large areas and population sectors that do not yet have access to electric power supplies, particularly in rural and remote areas. This, of course, contributes to the lack of education and health services in these areas and affects the possible development rates, particularly for women and children.

It is based on the above that ESCWA has put an emphasis on activities and studies that can assess the status of the electric power sector and support its development. Several studies were published during the period 1996-1999 on the assessment of electric grids interconnection (2) and privatization of the power sector in the ESCWA region (3).

Meanwhile, the ESCWA member countries are all enjoying tremendous renewable energy resources, while several renewable energy technologies for electricity generation are currently mature or approaching maturity and can be commercially available in the short to medium-term. In view of this and the objectives of the ESCWA Energy Issues Section's (EIS) Medium Term Plan to support the promotion of renewable energy resources in the region, the ESCWA Secretariat directed efforts towards promoting regional cooperation in the field of renewable energy (4) and initiated a set of studies to evaluate the potentials of different renewable energy technologies. In line with this, the 2000-2001 EIS work programme included a study on "Potential and prospects for renewable energy electricity generation." The study targets the evaluation of the potential and prospects for renewable energy contributions to the required electricity generating capacities in the ESCWA member countries. It also assesses the demand that can be initiated owing to power exchange through the existing interconnected electric grids and those that are to be established later on.

The study is published in three volumes evaluating the potential and prospects for electricity generation using the available renewable energy resources, particularly solar, wind and biomass. However, it has to be noted that solar energy resources are appropriately assessed in the region, but wind and biomass resource assessment activities have been very limited and need to be enhanced to facilitate appropriate evaluation of its potential. For this reason and the fact that developed technologies for all renewable resources are available as mentioned earlier, the study volumes were organized to reflect such given facts. Volume I presents an overview of the status of wind and biomass resources and electricity generating technologies, while volumes II and III (published in Arabic) present the outcome of the two studies on the potential and prospects for electricity generation using solar thermal and photovoltaic technologies.

This report (volume I) presents the outcome of a study performed by the ESCWA Secretariat on the status and potential of wind and biomass electricity generation, which is largely based on the contribution of ESCWA consultant Mr. Sami Zannoun, the former executive chairman of the New and Renewable Energy Authority (NREA) of Egypt.

The evaluation of the application potentials of wind and biomass electricity generating technologies as a part of the study has faced some difficulties in the process of data and information collection, especially in the field of biomass. It seems that none of the ESCWA member countries—including Egypt—has done enough work in the field of biomass, in particular for the purpose of evaluating the application potentials. During the course of the study, data and information about wind energy have been collected for Egypt, Jordan, Lebanon, Oman and Saudi Arabia based on different data resources, as will be discussed in the following report.

The report is presented in two parts—part one on wind electricity generation and part two on biomass electricity generation— and also provides an overview of the study that covers the following:

1. A survey on the available technologies, state-of-the-art costs and future prospects.

2. A review of available wind and biomass resources in the ESCWA region and development of criteria for evaluating application potentials in each case.

3. An overall assessment of the current development status and preliminary evaluation of application potentials in the region.

4. A set of recommendations for actions needed to initiate programmes for developing wind and biomass resources.

Chapter I presents an overview of the state-of-the-art future prospects for wind energy electricity with emphasis on the development status of wind electricity generation technologies, the current implementation status and the future prospects regarding the different system aspects.

Chapter II reviews the development of the installed capacities for wind electricity in the world and in countries in the region. It also assesses the future prospects of wind power and discusses the technical, economic and environmental aspects that govern its development.

Chapter III outlines the wind resource status and its potentials, the current development status and the future prospects for wind electricity in the ESCWA member countries.

Chapter IV presents the case of Egypt concerning the wind energy progress, procedures, criteria and methodology of wind resource assessment and application potentials based on which a definite long-term wind energy programme is formulated. Egypt's experience in this respect offers an excellent model with remarkable lesson learned that can be considered by other ESCWA member countries in the region.

Chapters V and VI present the efforts directed to biomass resource assessment and the survey on the biomass electricity and state-of-the-art technologies. The requirements for applications are presented together with the current development status in the ESCWA member countries. This assessment may contribute to other required efforts to be made in future by each ESCWA member country to evaluate the biomass application potentials.

Chapter VII provides the conclusion and set of recommended actions that will facilitate future development and utilization of the wind and biomass resources in the region.

PART ONE

WIND ENERGY ELECTRICITY GENERATION

I. WIND ELECTRICITY, RESOURCE POTENTIALS, SITES AND TECHNOLOGIES

Wind energy was used as a source of power for more than a century; however, during the industrial revolution, it was replaced by fossil fuels owing to the difference in costs and reliability. Following the 1970 oil crisis, interest in wind energy, as well as other renewable energy resources, was renewed and wind energy technologies were developed, demonstrated and field tested in different applications. Since then, particularly during the last two decades, wind energy technologies for electricity generation were tremendously developed and reached a remarkable state of technical maturity.

The wind electricity costs and reliability depend on the various site and local characteristics. The wind turbine capacities have been developed to reach between several hundred kilowatts to over 1 MW per turbine in the year 2001, with a total world installed capacity of around 16,400 MW.

This chapter presents an overview of the state-of-the-art technologies and future prospects of wind energy electricity with particular emphasis on the development status of wind electricity generation technologies, the current implementation status and the future prospects regarding the different system aspects.

A. THE WIND ENERGY'S RESOURCE POTENTIAL AND SITES

1. *Resource potentials*

The amount of electricity that can be produced by wind turbines at any specific site is dependent on the mean wind speed and its frequency of distribution. Table 1 shows widely-used classifications of wind resources in the United States that identify the different wind power classes (6).

TABLE 1. CLASSIFICATION OF WIND RESOURCES

Wind power class	Wind power density at 10 metres, W/m^2	Wind speed at 10 metres, m/s	Wind power density at 50 metres, W/m^2	Wind speed at 50 metres, m/s
1	0-100	0-4.4	0-200	0-5.6
2	100-150	4.4-5.1	200-300	5.6-6.4
3	150-200	5.1-5.6	300-400	6.4-7.0
4	200-250	5.6-6.0	400-500	7.0-7.5
5	250-300	6.0-6.4	500-600	7.5-8.0
6	300-400	6.4-7.0	600-800	8.0-8.8
7	400-1000	7.0-9.4	800-2000	8.8-1.19

Source: World Energy Assessment, "Energy and the challenge of sustainability", the United Nations Development Programme, the United Nations Department of Economic and Social Affairs, and the World Energy Council, September 2000.

Notes: W/m^2 = watt per square metre; m/s = metres per second.

Wind resources can be exploited in areas where wind power density is at least 400 watts per square metre (W/m^2) at 30 metres above the ground or 500 W/m^2 at 50 metres above the ground. Moreover, technical advances are expected to open new areas for development.

The global potential of power production using wind has been analysed in several studies that have estimated the theoretical potential of global wind energy resources at class 3 and above (in terms of electricity generation potential) bringing the total to around 500,000 terawatt hours per year (TWh/y).

In its 1994 assessment, the World Energy Council (WEC) estimated the theoretical global wind potential on the order of 480,000 TWh/y based on the following assumptions: globally, about 3×10^7 square kilometres (km^2) or 27 per cent of the earth's land surface of 107×10^6 km^2 is exposed to the annual mean wind speed of higher than 5.1 metres per second (m/s) at 10 metres above the ground (class 3 and higher). If it were possible to use this area for the installation of wind farms receiving a generating capacity of 8 megawatt electric per square kilometre (MWe/km^2), altogether 240 terawatt electric (TWe) of installed wind turbine capacity could be realized with a potential to generate 240 TWe x 2,000 terawatt hours per terawatt electric (TWh/Twe) per year or 480,000 TWh/year.

The WEC also suggests a more conservative estimate, assuming that for practical reasons just 4 per cent of the area exposed to wind speeds of higher than 5.1 m/s can be used for wind farms. This number of 4 per cent is derived from detailed studies of the potential wind power in the Netherlands and the United States. If the wind turbines have an average output of 2,000 megawatt hours per megawatt electric (MWh/MWe) per year, the global potential of onshore wind power production is estimated at some 20,000 TWh/year.

2. *Wind sites requirements*

The economics of wind power depend strongly on wind speed. The actual energy contained in the wind varies with the wind speed to the third power. However, actual wind turbines do not yield that much extra power at higher wind speeds. Even so, a high wind speed is essential for a viable wind energy project.

The starting point for any wind development, then, must be a windy site, but other factors come into consideration as well. Wind speed varies with height; the higher a turbine is raised above the ground, the better the wind regime it will be exposed to. This will benefit larger wind turbines, which are placed on higher towers. An additional benefit of larger turbines is that they tend to be more efficient.

The wind speed/height equation makes higher sites more attractive from a resource point of view. The top of a hill makes a better place for a wind farm than the bottom of a hill, although the sight of a row of turbines on the crest of a hill may not represent everybody's idea of something picturesque. However, hilly and mountainous sites are more inaccessible than lowland sites, therefore, construction costs are higher.

The earth's landmasses could provide an enormous amount of wind energy but an equally great wind resource exists offshore. Wind speeds tend to higher at sea and wind flows are smoother over the surface of water. Offshore wind development is most likely to be concentrated in shallow water close to land. The cost of building a project offshore is greater than for a similar project onshore. However, the greater wind speed and the low environmental impact make offshore development attractive.

Prospective developers of wind energy projects will normally be able to refer to wind surveys in most of the developed countries in order to identify prospective sites for wind farms. The wind data that are available in many countries may be less precise. However, countries are now taking more interest in wind resources, which may, in turn, encourage more precise data.

Once a potential site has been identified, it must be studied to confirm that it is suitable. Long- and short-term wind speed measurements will normally be needed to ascertain the wind regime. Only when these figures are available can the economics of the project be determined with any accuracy.

B. THE WIND TECHNOLOGIES FOR ELECTRICITY GENERATION

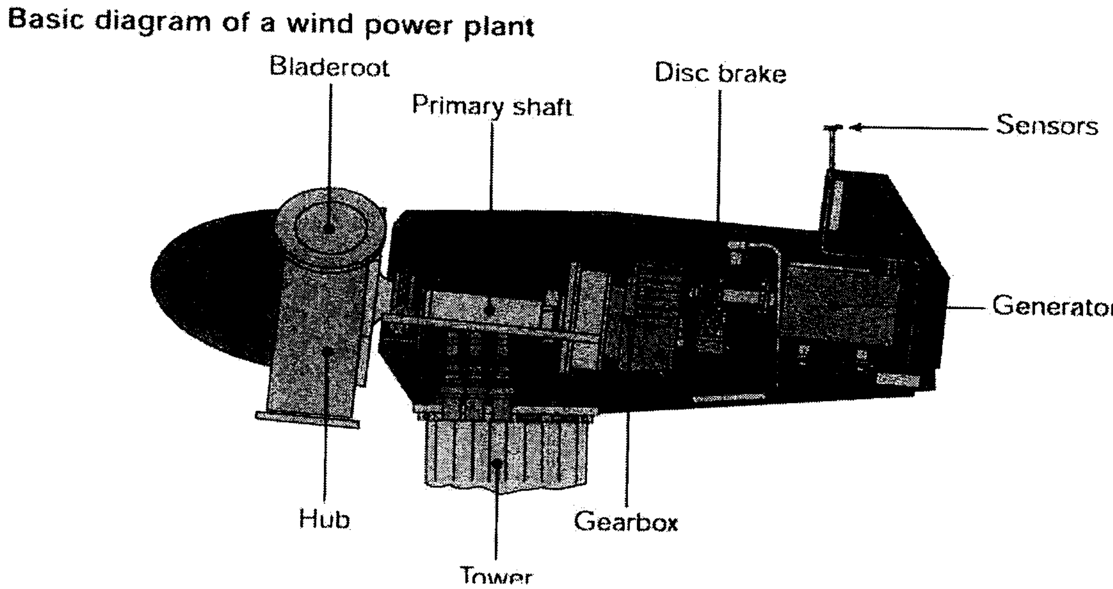
During the early part of the twentieth century, there were several important experiments implemented to determine the use of the wind to generate electricity, particularly in the United States and in Denmark. But it was not until the oil crisis of the early 1970s that modern interest in wind turbines was set in motion. The main centres of development were the United States—particularly in California—Denmark and Germany.

1. *Wind system components*

Figure I shows the basic wind energy conversion system as it has evolved for power generation applications and consists of a turbine rotor designed to capture the wind energy and convert it into mechanical energy in the form of rotation. The rotary motion is fed, normally via a gearbox, to a generator, which produces an electrical output. This output can be delivered into an electricity grid system. The combined rotor and nacelle are then mounted on top of a tower fitted with a yawing system so that the turbine rotor can be kept facing into the wind.

In view of the above, the following is a brief on the status of development of wind turbines and the systems classification.

Figure I. Components of basic wind energy conversion system



2. *Development of wind turbine sizes*

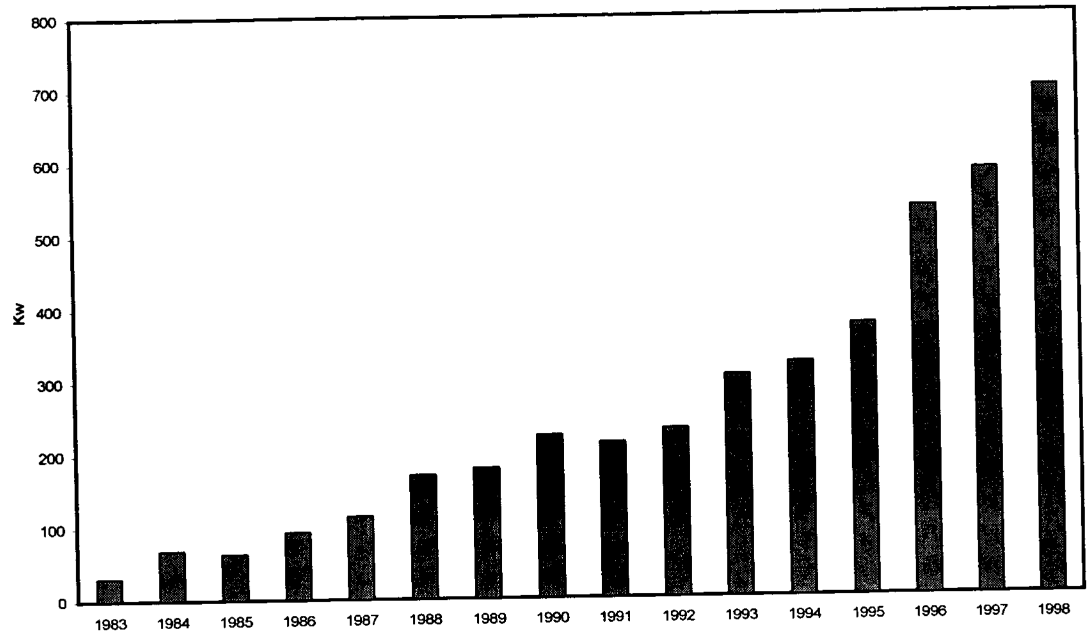
As a result of intensive basic and applied researches over the last 20 years, development and demonstration efforts are exceptional in several industrialized countries, with leading research centres and industries in Denmark, the Netherlands, the United States, Germany and others. The technologies of wind turbines for electricity generation are now in full progress, particularly with respect to turbine sizes, based on the development achieved during the last two decades.

The earlier versions of wind turbines that were developed for power generation in the late 1970s and the early 1980s had generating capacities of around 30-60 kW. Hundreds of machines of this size were installed at wind farms in the United States in the State of California. Through the 1980s and into the 1990s, wind turbine capacities increased steadily. During the 1980s, the standard turbine size tended to be between 300 kW and 500 kW, while during the 1990s, turbine unit size continued to increase steadily. By 1998, most new wind farms employed turbines with capacities of between 600 kW and 750 kW. For a number of reasons, modern, higher output machines tend to yield more energy than the smaller, older machines. Partly as a result of this, the trend towards even larger machines continues. Figure II shows the development of the average Danish wind turbine power rating in kilowatts between 1983 and 1998.

The main directives of future development is featured by the tendency towards higher ratings (multi-megawatts) and to achieve continued progress in controlling the quality of supply to satisfy any probable future conditions for the utilities.

Depending on the efficiency of the wind turbine, there is a cut-off wind speed below which wind power generation is not considered economical. This figure depends on the efficiency of the wind turbine design as well as on the turbine cost. For the type of turbine available in the late 1990s, this cut-off speed is at 6.5 m/s for a height of 25 metres above ground level and 7 m/s at 45 metres above ground level. Within the first decade of the twenty-first century, designs may be developed that make it economical to exploit sites with lower wind speeds.

Figure II. Average Danish wind turbine power rating in kilowatts



3. *Classification of wind turbines*

The available wind turbines in the world market can be sorted in different categories as follows:

(a) *According to horizontal or vertical axis*

The traditional wind turbine has the rotor attached to a horizontal shaft. This arrangement imposes certain restrictions on the wind turbine design. With a horizontal shaft, the rotor turns in a vertical plane and must be raised on a tower so that the blades do not strike the ground. Gearbox and generator are attached directly to the turbine shaft so these, too, must be placed on the tower, high above the ground. This raises the cost of both installation and maintenance. A horizontal axis machine must include a yawing system so that the rotor and nacelle can be rotated as the wind direction changes (7).

There is an alternative: a vertical axis wind turbine. A vertical axis machine has all its weight supported by a ground-level bearing. Both gearbox and generator can also be placed on the ground, easing maintenance costs. Most designs for a vertical axis wind turbine will operate with the wind blowing from any direction. A yawing system is unnecessary.

Several vertical axis designs have been tested since the 1960s. The most exhaustively explored was the Darrieus wind turbine, which comprises a pair of thin, curved blades with an aerofoil cross-section attached to a vertical shaft. A number of Darrieus wind turbines were built and tested—with capacities up to 1 MW—and developed in Canada. Other types of vertical axis turbines have also been built, however, the vertical configuration has not yet achieved significant commercial success.

(b) *According to power control systems*

(i) *Pitch-controlled wind turbines*

Pitch-controlled wind turbine technology allows the rotor blades to turn around on their longitudinal axis, where the turbine's electronic controller checks the power output of the turbine several times per second. When the power output becomes too high or too low, it sends an order to the blade pitch mechanism which immediately pitches (turns); the computer will generally keep the rotor blades at the optimum angle in order to maximize output for all wind speeds. The pitch mechanism is usually operated using hydraulics.

(ii) *Stall-controlled wind turbines*

Stall-controlled wind turbine technology is called passive stall-controlled where the rotor blades are bolted onto the hub at a fixed angle. The geometry of the rotor blade profile has been aerodynamically designed so that as the actual wind speed in the area increases, the angle of attack of the rotor blade increases, until at some point it starts to gradually stall.

The basic advantage of stall control is the avoidance of complex control systems, however, it causes induced vibrations. Around two thirds of the wind turbines currently being installed in the world are stall-controlled machines.

(iii) *Active stall-controlled wind turbines*

Active stall-controlled wind turbine technology is used in large wind turbines (more than 1 MW). Technically, this technology resembles the pitch-controlled machines, since they have pitchable blades in order to get a reasonably large torque at low wind speeds. The machines will usually be programmed to pitch their blades much like a pitch-controlled machine at low wind speeds. Often they use only a few fixed steps depending upon the wind speed.

The main differences between the active stall control and the pitch-control technologies are as follows:

a. If the generator is about to be overloaded, the machine will pitch its blades in the opposite direction from what a pitch-controlled machine does, i.e., it make the blades go into a deeper stall, thus wasting the excess energy in the wind;

b. One of the advantages of active stall control is that it can control the power output more accurately than with passive stall control so as to avoid overshooting the rated power of the machine at the beginning of a gust of wind;

c. Another advantage is that the machine can be run almost exactly at rated power at all high wind speeds. A normal passive stall-controlled wind turbine will usually have a drop in the electrical power output for higher wind speeds as the rotor blades go into a deeper stall. The pitch mechanism is usually operated using hydraulics or electric stepper motors.

d. Another theoretical possibility is to yaw the rotor partly out of the wind to decrease power. This technique of yaw control is in practice used only for tiny wind turbines (1 kW or less), as it subjects the rotor to cyclically varying stress that may ultimately damage the entire structure.

(c) *According to the type of tower*

Towers for large wind turbines may be one of three types (or a combination of the three): tubular steel towers, lattice towers or Guyed towers. Guyed tubular towers are only used for small wind turbines (battery chargers, etc.).

(i) *Tubular steel towers*

Most large wind turbines are delivered with tubular steel towers, which are manufactured in sections of 20-30 metres in length with flanges at either end and bolted together on the site. The towers are conical (i.e., with their diameter increasing towards the base) in order to increase their strength and to simultaneously save on materials.

(ii) *Lattice towers*

Lattice towers are manufactured using welded steel profiles. The basic advantage of lattice towers is cost, since a lattice tower requires only half as much material as a free-standing tubular tower with a similar stiffness.

The basic disadvantage of lattice towers is their visual appearance (although this issue is clearly debatable). Be that as it may, for aesthetic reasons, lattice towers have almost disappeared from use for large, modern wind turbines.

(iii) *Guyed pole towers*

Many small wind turbines are built with narrow pole towers supported by guy wire. The advantage is weight savings and consequently cost. The disadvantages include: difficult access around the towers, which make them less suitable in farm areas; and this type of tower is more prone to vandalism, thus compromising overall safety.

(iv) *Hybrid tower*

Some towers are made using different combinations of the techniques previously mentioned. One example is the three-legged Bonus 95 kW tower, which may be said to be a hybrid between a lattice tower and a guyed tower.

(d) *According to wind turbine generators*

Wind turbine generators are a bit unusual compared with other generating units ordinarily found attached to the electrical grid because the generator has to work with a power source (the wind turbine rotor) that supplies very fluctuating mechanical power (torque).

Wind turbines may be designed with either synchronous or asynchronous generators and with various forms of direct and indirect grid connection to the generator.

(i) *Synchronous generators*

Wind turbines that use synchronous generators normally use electromagnets in the rotor that are fed by direct current (DC) from the electrical grid. Since the grid supplies alternating current, it first has to convert alternating current (AC) to DC before sending it into the coil windings around the electromagnets in the rotor. The rotor electromagnets are connected to the current by using brushless and slip rings on the axle (shaft) of the generator.

Permanent magnet synchronous generators are not used very much because permanent magnets tend to become demagnetized by working in the powerful magnetic fields inside a generator and because powerful magnets are made of rare earth metals that are quite expensive.

Most wind turbines use generators with four and six poles. The reason for using these relatively high-speed generators is the savings on size and cost.

In another technique, larger numbers of poles are used to avoid the use of a gearbox (gearless machines).

(ii) *Asynchronous (induction) generators*

Most wind turbines in the world use a so-called three-phase asynchronous (cage wound) generator, also called induction generator, to generate alternating current. This type of generator is not widely used outside the wind turbine industry or in small hydro-power units. Nonetheless, the world has a lot of experience in dealing with it.

The curious thing about this type of generator is that it was really originally designed as an electric motor. In fact, one third of the world's electricity consumption is used for running induction motors driving machinery in factories, pumps, fans, compressors, elevators and other applications where needed to convert electrical energy to mechanical energy.

One reason for choosing this type of generator is that it is very reliable and tends to be comparatively inexpensive. The asynchronous generator also has some mechanical properties, which are useful for wind turbines (generator slip and certain overload capability).

The rotor moves with a negative slip, i.e., faster than the rotating magnetic field from the stator, which means that once again the stator induces a strong current in the rotor. The harder you crank the rotor, the more power will be transferred as an electromagnetic force to the stator and, in turn, converted to electricity that is fed into the electrical grid.

Asynchronous generators have a very useful mechanical property: the generator will increase or decrease its speed slightly if the torque varies. This means that there will be less wear and tear on the gearbox. Also, its stator requires magnetization from the grid—one of the important reasons for using asynchronous rather than synchronous generators.

These generators are further classified as follows:

a. *Two-speed, pole-changing generators*

Some manufactures fit their turbines with two generators: a small one for periods of low wind and a large one for periods of high wind.

A more common design on newer machines is pole-changing generators, i.e., generators that (depending on how their stator magnets are connected) may run with a different number of poles, and thus different rotational speeds.

Some electrical generators are custom-built as two-in-one, i.e., they are able to run as either 150 kW or 600 kW generators and at two different speeds. This design has become ever more widespread throughout the industry.

Whether it is worthwhile to use a double generator or a higher number of poles for low wind depends on the local wind speed distribution and the extra cost of the pole-changing generator compared with the price the turbine owner gets for the electricity.

A good reason for having a dual generator system, however, is that it may run at a lower rotational speed at low wind speeds. This is both more efficient (aerodynamically), and it means less noise from the rotor blades (which is usually only a problem at low wind speeds).

b. *Variable slip generators for wind turbines*

Manufacturers of electric motors have for many years been faced with the problem that their motors can only run at certain—almost fixed—speeds determined by the number of poles in the motor.

The motor (or generator) slip in an asynchronous (induction) machine is usually very small for reasons of efficiency, so the rotational speed will vary around 1 per cent between idle and full load.

The slip, however, is a function of the DC resistance (measured in ohms) in the rotor windings of the generator. The higher the resistance, the higher the slip, so one way of varying the slip is to vary the resistance generator slip to 10 per cent, for example.

For motors, this is usually done by having a wound rotor, i.e., a rotor with copper wire windings that are connected in a star shape and connected with external variable resistors, plus an electronic control system to operate the resistors. The connection is usually made with brushes and slip rings, which is a clear drawback over the elegantly simple technical design of cage-wound rotor machines. It also introduces parts that wear down in the generator, and thus the generator requires extra maintenance.

c. *Opti slip*

An interesting variation of the variable slip induction generator avoids the problem of introducing slip rings, brushes, external resistors and maintenance altogether. By mounting the external resistors on the rotor itself, and mounting the electronic control system on the rotor as well, you still have the problem of how to communicate the amount of slip you need to the rotor. This communication can be done very elegantly, however, using optical fibre communications, and sending the signal across to the rotor electronics each time it passes a stationary optical fibre.

d. *Generators running a pitch-controlled turbine at variable speed*

There are a number of advantages of being able to run a wind turbine at variable speeds.

One good reason for wanting to be able to run a turbine partially at variable speeds is the fact that pitch control (controlling the torque in order not to overload the gearbox and generator by the wind turbine blades) is a mechanical process. This means that the reaction time for the pitch mechanism becomes a critical factor in turbine design.

If you have a variable slip generator, however, you may start increasing its slip once you are close to the rated power of the turbine. The control strategy applied in widely used Danish turbine design (600 kW and up) is to run the generator at half of its maximum slip when the turbine is operating near the rated power. When a wind gust occurs, the control mechanism signals to increase generator slip to allow the rotor to run a bit faster while the pitch mechanism begins to cope with the situation by pitching the blades more out of the wind. Once the pitch mechanism has done its work, the slip is decreased again. In case the wind suddenly drops, the process is applied in reverse.

Although these concepts may sound simple, it is quite a technical challenge to ensure that the two power control mechanisms cooperate efficiently.

(e) *According to existence or absence of a gearbox*

(i) *Wind turbine with gearbox*

The gearbox is necessarily used between the lower speed turbine rotor and the higher speed asynchronous (induction) generator. It raises the revolutions of the generator to the synchronous speed required to produce electric energy at the industrial frequency. The generator speed depends on the number of poles.

(ii) *Gearless wind turbines*

These turbines should drive synchronous generators designed with a suitable number of poles. Gearless wind turbines mean direct drive, using a permanent magnetic variable-speed disk generator. Its advantage is the compactness and higher performance of the wind turbine. The large number of poles of the generator is essential to avoid the need for a gearbox.

4. *Wind farms*

To take full advantage of the wind, wind turbines are usually deployed in groups ranging from two or three turbines to several hundred. These groupings are commonly known as wind farms. When grouped together, wind turbines are usually spaced between 5 and 10 times their rotor diameter apart in order to reduce interaction between adjacent machines.

When machines are operating downwind of one another, there will usually be some loss of output from the downwind turbines. When this spacing is taken into account, a wind farm consisting of 20 x 500 kW turbines will occupy an area of 3-4 km^2. Of this, only around 1 per cent is actually taken up by the turbines. The remainder can still be used as farmland.

Such a concept (wind farms) has promoted the use of wind electricity generation to large-scale grid-connected applications. However, the maximum wind power that can be connected to a specific grid depends on the grid capacity and the permissible wind penetration rate (usually between 10-15 per cent of the grid capacity). Such wind energy is that which the national transmission systems can accept while still operating reliably.

II. WIND ELECTRICITY, INSTALLED CAPACITY, DEVELOPMENT, PROSPECTS AND SYSTEM ASPECTS

A. DEVELOPMENT OF INSTALLED CAPACITIES

Wind power has enjoyed fast-paced development in recent years, mostly in the industrialized world, with Germany, the United States, Spain and Denmark emerging as the fastest growing wind markets worldwide in 1999. In April 1999, the American Wind Energy Association (AWEA) and the European Wind Energy Association jointly announced that the world's total installed wind capacity had exceeded 10,000 megawatts (MW). In addition, more than 3,600 MW of newly installed electricity-generating capacity in 1999 brought the world total to around 13,400 MW. Such increase is the largest addition to global wind capacity ever in a single year, with a 36 per cent increase from 1998. Germany, the United States and Spain alone accounted for more than 40 per cent of total increase in capacity (8).

Table 2 and figure III below highlight the development of the operating wind power capacity between 1995 and January 2001 (9, 10).

1. *The United States*

Wind energy projects enjoyed a resurgence in 1999 after several years of lackluster growth. Developers rushed to install wind energy facilities before the threatened elimination of Federal production tax credits for wind power, which expired in June 1999, although legislation was recently passed to extend the provision until 31 December 2001. Under this provision, wind power producers are allowed to claim a tax credit of $0.017 per kilowatt-hour of electricity produced. Wind developers accelerated installations to qualify for the 10-year period of tax incentives, and the United States wind capacity surged in 1998 and 1999 with more than US$ 1 billion worth of new generating equipment, representing some 1,073 megawatts.

The United States wind industry installed about 892 megawatts of new projects and 181 megawatts of re-powering projects between June 1998 and June 1999. The added wind capacity was more than double the previous annual record in 1985 for the United States, when about 400 megawatts were installed.

More than half the new wind projects in 1999 for the United States were installed in Minnesota and Iowa. In Minnesota, a 1994 State law requires the State's largest utility to install 425 megawatts of wind power by 2002; in Iowa, its 1983 law requiring utilities to obtain 2 per cent of their total electricity from renewables accounted for most of the State's 240 megawatts of additional wind capacity. Other States adding new wind projects include Texas (146 megawatts), California (117 megawatts), Wyoming (73 megawatts), Oregon (25 megawatts), Wisconsin (23 megawatts), and Colorado (16 megawatts) (9).

2. *Europe*

At the end of 1998, Spain had installed more than 820 megawatts of wind capacity, adding an additional 650 megawatts in 1999. The Spanish National Energy Plan targets a 25 per cent increase in renewable energy use over 1990 levels by the year 2000. The December 1998 Royal Law 2826/1998 sets the target that renewables should account for at least 12 per cent of the country's energy demand by 2010.

In Sweden, in order to compensate for electricity that will be lost when Sweden closes its Barseback nuclear reactors by mid-2001, the country expects to increase the use of renewables, along with promoting energy conservation. To that end, some $1.3 billion (1996 U.S. dollars) will be invested in long-term development of biofuels, ethanol, wind, solar and other renewable sources.

The United Kingdom of Great Britain and Northern Ireland had installed by mid-1999 some 340 megawatts of wind capacity. The country has an official goal of generating 10 per cent of its electricity demand from renewable energy sources by 2010; however, a 1999 report issued by the United Kingdom's Parliament House of Lords stated that while it would be "technically feasible" to achieve this goal, "present policies will not deliver them." The report states that achieving the 2010 target would require a sevenfold increase over the next 10 years in the rate of expanding renewable energy generation. To help stimulate the development of renewable electricity generation, the Government of the United Kingdom requires electricity suppliers to provide a portion of their supply from renewable sources.

In addition, many countries of Western Europe have recently passed legislation to support the development of alternative energy sources in the form of taxes that are to be used specifically for renewable resources that would not otherwise be available to develop them. For example:

Denmark introduced the Energy 21 programme—its fourth energy policy plan—in 1996. Energy 21 sets a national objective to reduce the country's carbon emissions by 20 per cent below their 1988 level by 2005. The Danish government since 1992 has imposed a carbon tax of about $14.20 (DKr 100) per metric ton of carbon dioxide emitted, which was fully refundable to industrial consumers at first but was limited to 50 per cent in 1993. Energy 21 includes a target for the installation of 1,500 megawatts of wind capacity by 2006. By 1998, Denmark had already installed an estimated 1,467 megawatts of wind power, representing 12 per cent of the country's total electricity consumption. Energy 21 sets a target of 5,500 megawatts of installed wind capacity by 2030, with 4,000 megawatts slated for offshore installation.

A Green Tax Package for industrial consumers was also introduced by the Danish government in 1996, part of which included the taxation of space heating for carbon emissions and sulfur dioxide emissions, in combination with a refund in the form of subsidies for installation of energy-saving measures. The tax package will be fully phased in by the end of 2000.

In Germany, the government has substantially increased its wind-generated electricity production in recent years. In 1998, consumption of electricity from wind power in Germany exceeded that in the United States for the first time, as Germany installed 800 megawatts of new wind capacity to bring its total to 2,800 megawatts. Germany was the world leader in wind capacity additions in 1998. Although no specific targets have been set for increasing wind capacity, the government has set a target to reduce carbon dioxide emissions by 25 per cent relative to 1990 levels by 2005 and believes that wind will contribute to meeting that goal. Two German States—Lower Saxony and Schleswig-Holstein—have plans to increase wind capacity to 1,000 megawatts by 2000 and 1,200 megawatts by 2010, respectively. A number of government programmes support the development of renewables in Germany.

3. *Arab countries*

During the last decade, with the exception of Egypt and Morocco, very little has been done to tap into wind energy for electricity generation in the Arab countries, including ESCWA member States.

In Egypt, there has been some movement in bringing wind power to the country. In addition to the current implementation status described in chapter III of this report, the Japanese government in 1999 announced that it would extend soft credits to fund a US$ 120 million, 120-megawatt wind facility in the Zafarana region on the Gulf of Suez. The terms of the agreement include that it may be repaid over a 40-year period, with a 10-year grace period, at an annual interest rate of 0.75 per cent. In March 1999, Spain committed to financing a 60-megawatt wind power plant in Zafarana.

In Morocco, the country advanced a number of renewable energy initiatives. In October 1999, one issued a tender for US$ 200 million for the construction of two wind farms—a 140-megawatt project in Tangiers near the Strait of Gibraltar.

4. *In Asia*

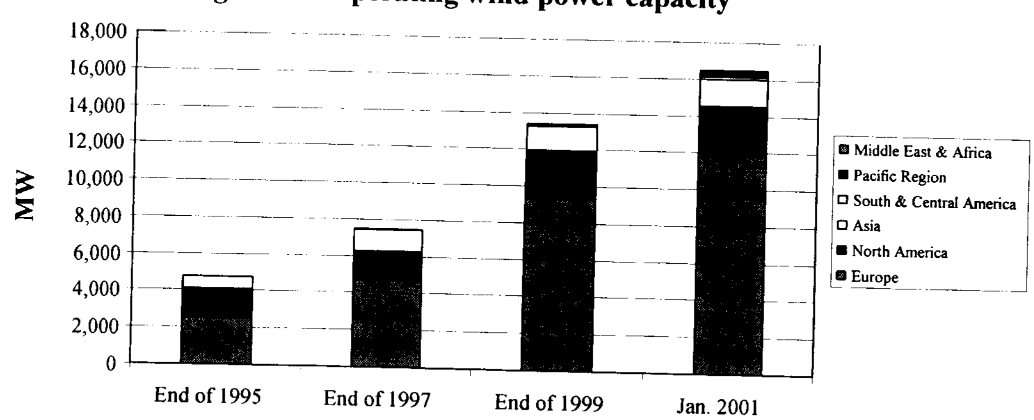
The development of renewable energy sources in industrialized Asia (Japan, Australia and New Zealand) has not increased dramatically in recent years. Consumption of renewable energy in industrialized Asia is projected to grow by 1.2 per cent per year over the next 23 years.

TABLE 2. OPERATING WIND POWER CAPACITY (MW)

	End of 1995	End of 1997	End of 1999	January 2001
Europe				
Germany	1 136	2 080	4 445	5 432
Denmark	619	1 116	1 742	2 281
Spain	145	512	1 530	2 099
Others	618	969	1 590	2 019
Subtotal	2 518	4 677	9 307	11 831
Middle East and Africa				
Egypt	5	5	15	65
Morocco	0	0	0	54
Others	7	19	24	24
Subtotal	12	24	39	143
Pacific Region				
Japan	5	18	68	150
Australia	10	11	11	32
New Zealand	2	4	37	37
Subtotal	17	33	116	219
Asia				
India	565	950	1 095	1 150
China	44	166	182	302
Others	0	0	10	14
Subtotal	609	1 116	1 287	1 466
North America				
United States of America	1 591	1 584	2 492	2 568
Canada	21	23	127	140
Subtotal	1 612	1 607	2 619	2 708
South and Central America				
Costa Rica	0	20	46	51
Brazil	2	3	20	20
Others	9	15	21	23
Subtotal	11	38	87	94
World total	4 779	7 495	1 3455	16 461

Source: Windpower Monthly News Magazine, vol. 13, No. 4, April 1997.

Figure III. Operating wind power capacity



In Australia, plans for wind projects have been hampered by complaints and protests from local residents who do not like the noise or the visual distraction of wind farms. The Australian Federal Cabinet deferred a decision on a government proposal to require that an extra 2 per cent of energy needs to be provided with renewable energy sources.

In Japan, a large wind power plant became fully operational in 1999. The Hisai City, Mie Prefecture, site has four 750-kilowatt turbines, but the 3-megawatt plant represents only a small fraction of the 211,000 megawatts of total electric power capacity currently installed in the country.

In China in 1999, the World Bank approved its largest-ever renewable energy loan and its first renewable energy loan for China—US$ 100 million. The Global Environment Facility (GEF) is providing an additional US$ 35 million grant. The aims of the project are to develop wind power in the provinces of Inner Mongolia, Hebei, Fujian, and to develop solar power in isolated rural areas in the northwest of the country for the first time on a large-scale and competitive basis. Upon completion, China's project will amount to 400 megawatts of wind power (as compared with 700 megawatts in India).

For the wind portion of the project, the World Bank is providing funds to the State Power Corporation of China and provincial and/or municipal companies, which in turn will hire wind farm companies to install a total of 190 megawatts of wind capacity at five sites. All five projects are tentatively scheduled to be completed within 4 years. Each wind farm will be developed on a commercial basis, using power purchase agreements (PPAs) that are meant to pave the way for eventual private sector participation in future wind power projects. The World Bank is funding this project mainly to help China reduce its greenhouse gas emissions, especially carbon emissions.

In India, wind industry development has fallen off sharply since 1995 because of the imposition of new taxes, an economic slowdown, and bureaucratic delays in land allotment and environmental clearances. The government is, however, working on new measures to secure private-sector investment in wind projects. In July 1999, the government proposed several incentives to help boost wind power development, including withdrawal of the minimum tax on renewable energy projects, automatic environmental clearances for units of generation capacity up to 5 megawatts, and softer loans.

5. *Canada*

There have been some attempts to increase the use of wind-generated electricity in Canada, but the use of wind and other alternative renewables remains low. In 1999, Canada had a total of 83 megawatts of installed wind capacity in seven facilities, both on and off the national power grid. The Canadian Wind Energy Association estimated that the wind energy capacity operating by 2000 in Canada reached 133 megawatts, and the electricity produced is sold to the local Utilities Corporation under long-term contracts.

B. FUTURE PROSPECTS

1. *Projected wind power capacities*

Several studies have developed different generic scenarios to assess the growth of wind power in the coming decades. They address three main questions: Can wind power contribute 10 per cent of the world's electricity needs within three decades? How long will it take to achieve this? How will wind power be distributed throughout the world?

The recent trends scenario extrapolates critical market development, while the international agreements scenario assumes that international agreements are realized. Both scenarios assumed that integrating up to 20 per cent of wind power in the grid (in energy terms) would not be a problem with present grids, modern fossil fuel power plants, and modern wind turbines. Analysis of the world's exploitable wind resources, with growth of electricity demand as indicated in the International Energy Agency (IEA) World Energy Outlook (8), led to the following conclusions:

(a) *Under the recent trends scenario*

Starting with 20,000 MW by the end of 2002 and assuming a 15 per cent cost reduction, and later 12 per cent, for each doubling of the accumulated number of installations, 10 per cent penetration would be achieved around 2025, and saturation would be achieved between 2030 and 2035 at about 1.1 terawatts (TW). In this scenario, the cost of generating wind electricity would come down to $0.032 per kilowatt hour (kWh) on average (1998 level), depending on wind speed, connection costs to the grid, and other considerations.

(b) *Under the international agreements scenario*

With the same starting conditions as listed in the recent trends scenario above but with a slightly different learning curve, growth is faster and 10 per cent penetration would be achieved around 2016, with saturation being achieved between 2030 and 2035 at about 1.9 TW. In this scenario, the cost would come down to $0.027 per kWh on average.

In the second scenario, the regional distribution of wind power in North America is 23 per cent, Latin America 6 per cent, Europe (Eastern and Western) 14 per cent, Asia 23 per cent, Pacific Organization for Economic Cooperation and Development (OECD) 8 per cent, North Africa 5 per cent, former Soviet Union 16 per cent, and the rest of the world 5 per cent.

2. *Technology developments*

The main technology development features expected in the coming decade based on the achieved development trends since the 1970s are:

(a) *Wind turbines become larger*

Since the mid-1970s, there has been a gradual growth in the unit size of commercial wind turbines (see table 3). In mid-1978, the typical size of a wind turbine was 30 kilowatts of generating capacity, with a rotor diameter of 10 metres. The largest units installed in 1998 had capacities of 1,650 kilowatts with rotor diameters of 66 metres. By 1999, 460 units with a generating capacity of 1 megawatt or more were installed worldwide.

Market demands drive the trend towards larger machines: Economies of scale, less visual impact on the landscape per unit of installed power, and expectations that offshore potentials will soon be developed are also expected. The average size of wind turbines installed is expected to be 1,200 kW before 2005 and 1,500 kW thereafter. Note, however, that the optimum size of a turbine—including cost, impact and public acceptance—differs for onshore (nearby as well as remote) and offshore applications.

TABLE 3. INSTALLED WIND TURBINES, 1992-1999

Year	Size (kilowatt)
1992	200
1994	300
1996	500
1998	600
1999	700

(b) *Wind turbines become more controllable and grid-compatible*

The output of stall-regulated wind turbines is hardly controllable, apart from switching the die machine on and off. Output varies with the wind speed until the rated wind speed value is reached. As the ratio of the aerodynamic stall phenomena to structural compliant machines gets more difficult with bigger turbines, blade pitch control systems are being applied to them. For structural dynamics and reliability, a blade-pitch system should be combined with a variable speed electric conversion system. Such systems typically incorporate synchronous generators combined with electronic AC-DC-AC converters.

Modern electronic components have enabled designers to control output—within the operational envelope of die wind speed—and produce excellent power quality. These developments make wind turbines more suitable for integration with the electricity infrastructure and ultimately for higher penetration. These advantages are of particular interest for weak grids, often in rural and remote areas that have a lot of wind.

(c) *Wind turbines will have fewer components*

For lower costs and greater reliability and maintainability, designers now seek technology with fewer components, such as directly driven, slow-running generators with passive yaw and passive blade-pitch control. In Germany, 34 per cent of the installed power in 1998 (770 megawatts) was rehashed with this type of technology.

Special offshore designs are on the drawing board. With the first offshore wind farms in Europe, industrial designers are developing dedicated turbine technologies for large wind farms in the open sea (Beurskens 2000). Outages onshore can often be corrected quickly so that only a small amount of energy is lost. But offshore, repairs or replacing components is often high. Offshore design features will include installation concepts, electricity conversion and transport systems, corrosion protection, and integration with external conditions (both wind and wave loading).

(d) *Time to market is becoming shorter than project preparation time*

Although there is a temporary shortage of supply of wind turbines in some countries, competition among manufacturers is fierce. One way to become more competitive is to keep implementing component improvements to reduce costs. Time to market new products is also becoming short (two to three years). Just as the construction of a wind farm commences, the technology is already outdated.

C. System aspects

There are a number of technical, economic and environmental aspects that would govern the development of wind power projects. They include:

1. *The technical aspects*

(a) Wind turbines deliver energy, but little capacity. Because wind energy is intermittent, wind turbines mainly deliver energy but little capacity, its value often 20 per cent or less of the installed wind power. This percentage decreases when the penetration of wind turbines increases, requiring even more back-up power for a reliable energy;

(b) Wind power becomes more predictable. Meteorological research on predicting the output of wind farms a few hours in advance has produced computer programs that optimize the operational and fuel costs of regional electricity production parks (Denmark, Germany). This will increase the capacity value of wind power and the value of the electricity produced;

(c) Capacity factors are somewhat adjustable. Some general misconceptions sometimes lead to the wrong decisions or conclusions. The capacity factor (annual energy output/output based on full-time operation at rated power) depends on local winds and wind turbines. By optimizing the turbine characteristics to the local mind regime, the capacity factor—now often 20-25 per cent—can be optimized without losing too much energy output. But extreme capacity factors—say, 40 per cent—automatically means a large loss of potential energy output.

2. *The cost and economic aspects*

The energy generation costs of wind turbines are basically determined by five parameters:

(a) *Turnkey project costs*

Initial investment costs (expressed in US dollars per square metre of swept rotor area), project preparation, and infrastructure make up the turnkey project cost. The costs of European wind turbines are typically US$ 410 per square metre (machine cost, excluding foundation). Project preparation and infrastructure costs depend heavily on local circumstances, such as soil conditions, road conditions, and the availability of electrical substations, as well as labour costs. Turnkey costs vary from US$ 460 per square metre to US$ 660 per square metre. However, the average cost per kilowatt installation varies between US$ 1,000 and US$ 1,100.

The cost of wind turbines has fallen significantly. According to an April 1997 article written by David Milborrow in *Windpower Monthly*, the cost of Danish wind turbines dropped from around 1,050 European currency (ECU) per kW in 1992 to ECU 724/kW (around US$ 724/kW) in 1996, a decline of 30 per cent.

German wind turbines tend to be more expensive than those manufactured in Denmark. According to Milborrow, German prices fell by only 15 per cent between 1992 and 1996 to ECU 9OO/kW.

Total capital costs for wind farm construction have fallen in line with the fall in the cost of turbines. The United Kingdom capital costs between 1992 and 1996 fell by around 20 per cent from 1,000 pounds sterling (£) per kW to £ 800/kW (US$ 1,200/kW).

(b) *Energy of the system*

The energy output of a wind turbine can be estimated by the equation $E = b. V^3$ kilowatt-hours per square metre, where E is the annual energy output, b is the performance factor, and V is the average wind speed at hub height. The factor b depends on the system efficiency of the wind turbine and the statistical distribution of wind speeds. In coastal climates, a value of 3.15 for b is representative of modern wind turbines and too far away from a theoretical maximum. Figure IV shows the effect of wind speeds on generated electricity costs.

(c) *Local average wind speed*

In general, local average wind speed should exceed 5 metres per second (m/s) at a height of 10 metres to allow economic exploitation of grid-connected wind turbines.

(d) *Availability of the system*

The technical availability of modern wind farms exceeds 96 per cent.

(e) *Lifetime of the system*

Design tools have improved so much. As a result, one confidently use lifetimes of 15-20 years for economic calculations

Figure V illustrates the cost reductions for electricity generation from wind turbines in Denmark since 1981, however, it will vary for other regions based on variables of cost of project preparation, infrastructure and civil works. Some recent Danish studies expect a 35-45 per cent reduction in generation costs in the next 15-20 years (figure VI).

3. *The environmental aspects*

The primary environmental advantages of wind power are that it is renewable, so it does not deplete a global resource and it does not produce any harmful byproducts. If wind power is assumed to replace other types of power generation, then a 1 MW wind farm in the United Kingdom will prevent the production of 2,200 tons of carbon dioxide (CO_2), 30 tons of sulphur dioxide (SO_2) and 10 tons of nitrogen oxides (NO_x) each year. These figures from ETSU are based on the generation mix in the United Kingdom in 1990—a computation assuming the displacement of fossil fuel generated power alone would provide larger savings.

Against this must be balanced the environmental impact of wind power. The main considerations are visual impact and noise. Wind farms cover a large area and they are impossible to hide. Actual land use is low and the area occupied by a wind farm can be used for other purposes too. However, the sight of an array of wind turbines, often in otherwise undeveloped rural areas, is considered by many to be visually offensive. The weight to be placed on the visual impact of wind power development will vary from site to site and from community to community; it is virtually impossible to quantify. Nevertheless, it will restrict the available sites for wind power development.

The other major effect of a wind turbine is that it generates a noise which may limit the possible sites for wind power development. However, the constant frequency is likely to make it more intrusive than the sound of the wind. To this rotor noise must be added the mechanical noise emanating from the gearbox and generator. Turbine noise is generally more intrusive when wind speeds are low. It will be masked by background noise, provided the machine is far enough away from human habitation. This, again, will limit the possible sites for wind power development.

4. *Wind system risks*

Two primary sources of risk can be attached to wind power: the risk associated with the reliability of the wind power resource available at a particular site, and the risk attached to the use of wind power equipment.

The wind resource risk—the risk that the wind will not blow as it was expected to—should be minimal provided an adequate feasibility study has been performed. While the strength of the wind on a particular day at a particular site cannot be predicted, wind is normally reliable over longer periods. A windy site will not turn into a windless site.

Wind turbine technology is less certain. While the industry is now well established and many design features have been proven, development is continuous and that always carries a certain risk. Wind turbines are becoming larger; the larger machines are necessarily newer and therefore experience with them is limited. When choosing wind turbines for a commercial operation, it is vital to obtain historical performance data to establish its reliability. Catastrophic failure is not unknown within the wind power industry. It may be possible to insure against damage and failure. This represents one way of mitigating the risk but it will increase the overall cost of generation.

While wind power generation is seen as new, it is bound to be viewed by financial markets as uncertain. This uncertainty will translate into higher cost of loans. As wind turbine technology matures, this situation will improve.

Figure IV. Effect of wind speed on generated electricity cost

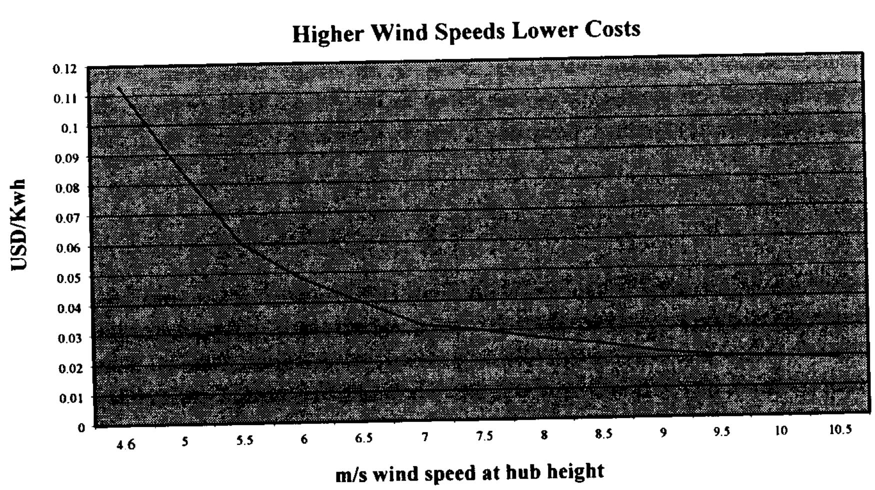


Figure V. Development of wind electricity generation costs in Denmark

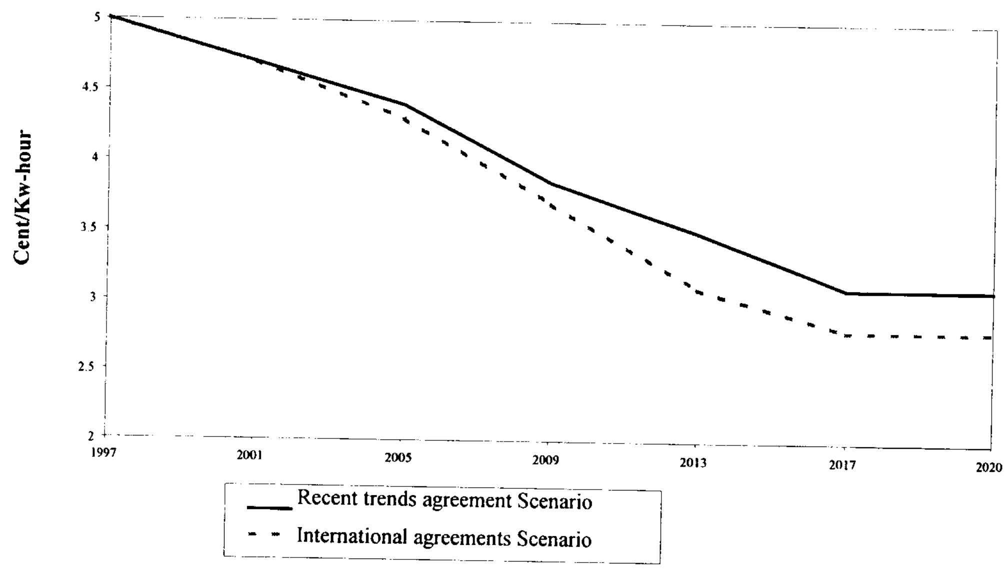
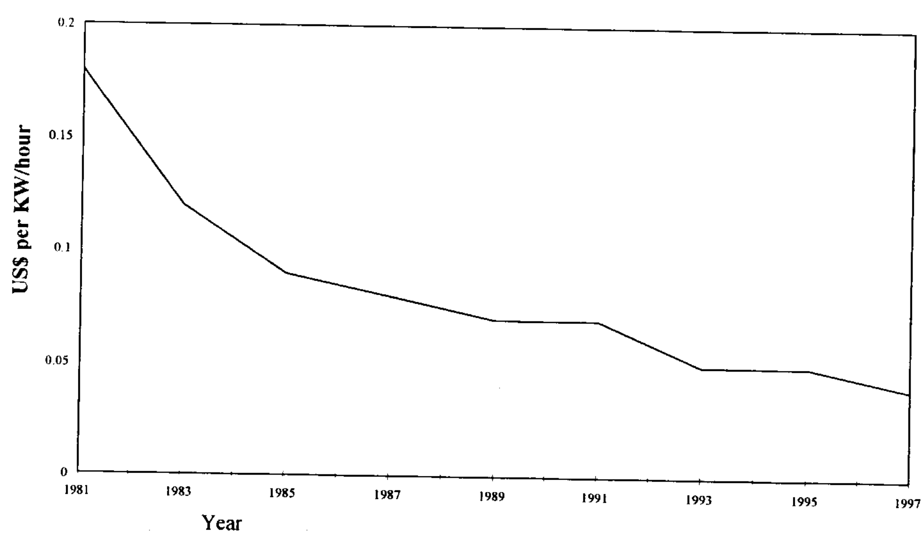


Figure VI. Potential cost reductions for wind power, 1997-2020



III. POTENTIALS OF WIND ELECTRICITY IN THE ESCWA REGION

A. BACKGROUND

Since the mid-1970s, several ESCWA member countries have directed their interest towards the development of wind energy systems, both for mechanical pumping and electricity generation. These countries include Egypt, Jordan, Saudi Arabia, the Syrian Arab Republic and Yemen. For electricity generation, with the exceptions of Egypt and Jordan, the activities were limited to resource assessment or very low capacity projects, which are not being implemented within any national planned programme.

This chapter outlines the wind resource status and potentials, the current development status and the future prospects for wind electricity in the ESCWA member countries.

B. WIND RESOURCES STATUS

Wind resource measurements are regularly taken by most of the meteorological organizations in the ESCWA member countries. However, they are not as precise as to satisfy the requirements for wind statistics for energy assessment. Accurate estimates of expected annual wind energy production from wind farms are necessary to facilitate the comparison of different alternative electricity generation options needed for investment decisions, as well as for site selection and design of wind farms.

The data obtained from the national weather stations could be used to determine the overview of the wind energy potential in the ESCWA member countries (course wind assessment). In order to establish a wind energy programme, a wind resource assessment programme should be adopted by each ESCWA member country in order to provide high-quality and accurate wind data.

In view of the above and based on the information collected from different resources (12, 13, 14, 15, 16), wind resource assessments have been undertaken by several ESCWA member countries. However, the depth of the data collected and its analysis differ from one country to another. Most of the available data are incomplete and can only be used for a general description of wind resources rather than for evaluating it. Only Egypt, Jordan, Saudi Arabia and the Syrian Arab Republic have devoted detailed efforts but each deriving different levels of details. The results of these efforts are described below.

1. *Egypt*

Egypt began a preliminary assessment of its wind energy resources in 1972 and consequently stepped up its efforts in the early 1980s by installing a network of wind measuring stations at different sites. The following publications were prepared as a result of such efforts and will be detailed in chapter IV.

(a) *Egypt's Preliminary Wind Map* (shown in figure VII) was developed in 1986 through the renewable energy testing project financed by the United States Agency for International Development (USAID). The Map shows three areas where winds are high in Egypt, particularly the Red Sea coast, the western section of the Mediterranean coast, and East Oweinat;

(b) *The Wind Atlas* for the Gulf of Suez was published in 1997 by the Riso National Laboratory, Denmark, and the NREA. It presents average hourly variations in wind speed that represent a "typical" day for each month, wind frequency curves and annual average speeds, and that provide a wind rose (a map/diagram summarizing the frequency and strength of the wind from all eight compass directions). The data were obtained from four measuring stations (24.5 metres high and installed at Abu-Darag, Zafarana, Ras el-Behar and Hurghada, extending from latitude 27° 19°N latitude 29° 17°N (11). The highest average annual wind speeds range from 6.9 m/s in Hurghada, 8.9 m/s in Zafarana, 9 m/s in Abu-Darag, 9.1 m/s in Ras el-Behar, and 10.6 m/s at the Gulf of Ei-Zayt. The overall averages range from 4.5 m/s on the Mediterranean Coast to about 7 m/s in eastern Oweinat.

Currently, the NREA and the Danish International Development Agency (DANIDA) are further developing *The Wind Atlas* to cover the whole country. For more details, see chapter IV and annex I.

2. *Jordan*

In the late 1980s, the Royal Scientific Society (RSS) and the Ministry of Energy and Mineral Resources established a wind resource assessment programme. Through this programme, 30 measuring stations were installed at sites throughout Jordan to map wind energy resources. The highest recorded annual average wind speeds are found in the northern part of the country (5.5 to 7 m/s at a height of 50 metres). In 1989, Jordan's Ministry of Energy and Mineral Resources and Meteorological Authority, in cooperation with the Riso National Laboratory in Denmark, developed and published a preliminary wind atlas based on data collected from measuring stations around Jordan. It has been based on data collected at 36 meteorological stations. All data analysis has been performed using the Wind Atlas Application Programme (WAsP) in which the wind areas have been identified for potential wind energy (as shown on the wind map of Jordan in figure VIII), particularly in the northern area of the country with an average annual wind speed between 6.5 and 7.5 m/s. In addition, the southern areas enjoy good wind speed, while the eastern regions have significant wind potential.

3. *Saudi Arabia*

The Wind Energy Atlas of Saudi Arabia was published in 1986 by the King Fahd University of Petroleum and Minerals within the framework of the United States/Saudi cooperation programme "SOLARAS." Table 4 and figure IX show the mean annual wind speeds in different areas of the Kingdom of Saudi Arabia, which show that the available wind speeds are not in the utilizable range for electricity generation. The mean annual speeds vary between 2.5 m/s at Bisha to a maximum of 4.5 m/s at Dhahran.

TABLE 4. SAUDI ARABIA'S MEAN WIND SPEED (M/S)

Station	Annual	January-March	April-June	July-September	October-December
Badanah	3.8	3.9	4.5	3.7	2.9
Bisha	2.5	2.4	2.5	2.7	2.4
Dhahran	4.5	4.4	5.1	4.4	3.9
Al-Qasim	2.9	3.0	3.4	2.7	2.5
Jizan	3.5	3.4	3.5	3.8	3.2
Hail	3.1	3.3	3.4	2.8	2.7
Jeddah	3.5	3.7	3.7	3.5	3.0
Mabinah	3.7	3.9	3.8	3.7	3.3
Najran	2.8	2.4	3.0	3.6	2.2
Qaisumah	4.2	4.3	4.6	4.3	3.5
Rafah	3.4	3.8	3.8	3.0	2.8
Riyadh	3.5	3.7	3.9	3.6	2.7
Tabuk	3.0	3.0	3.5	3.1	2.3
Taif	3.9	3.7	3.8	4.8	3.1
Yanbu al-Bahr	4.4	4.3	4.8	4.7	3.9

Source: *The Wind Atlas of Saudi Arabia*.

Figure VII. Egypt's preliminary wind map

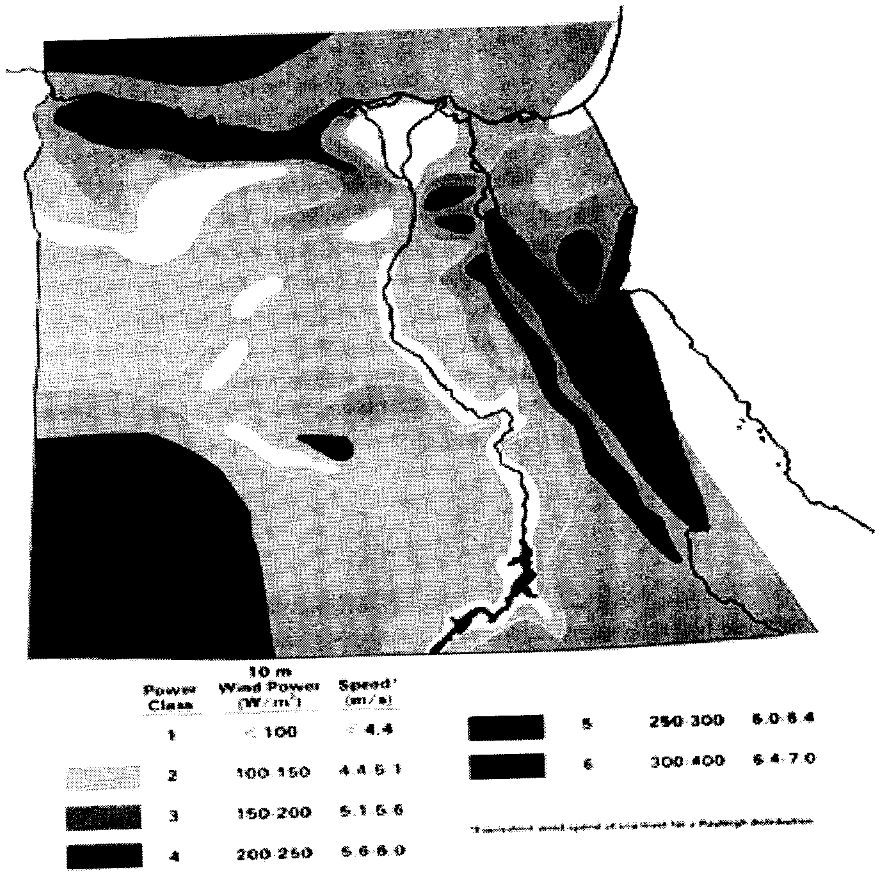


Figure VIII. Wind map of Jordan

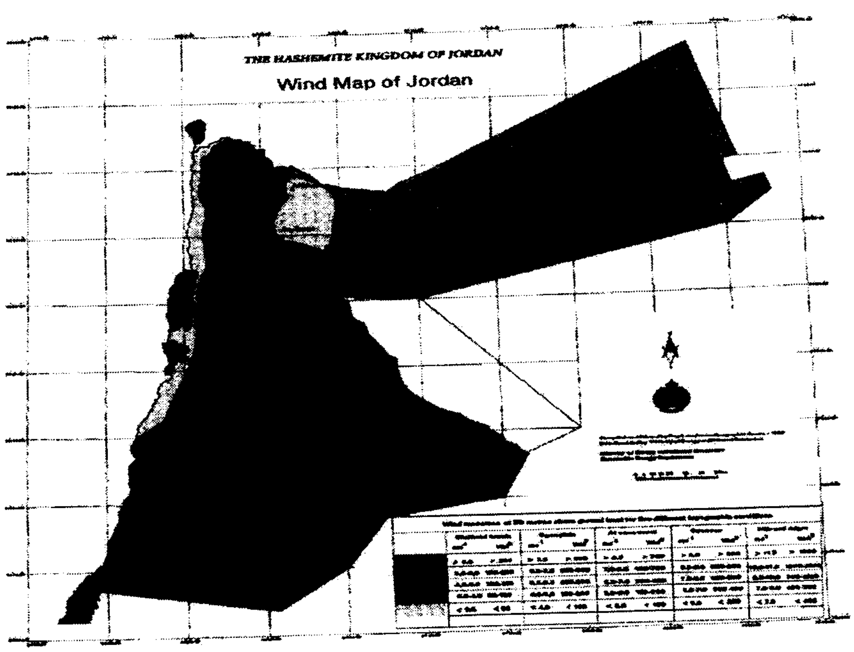
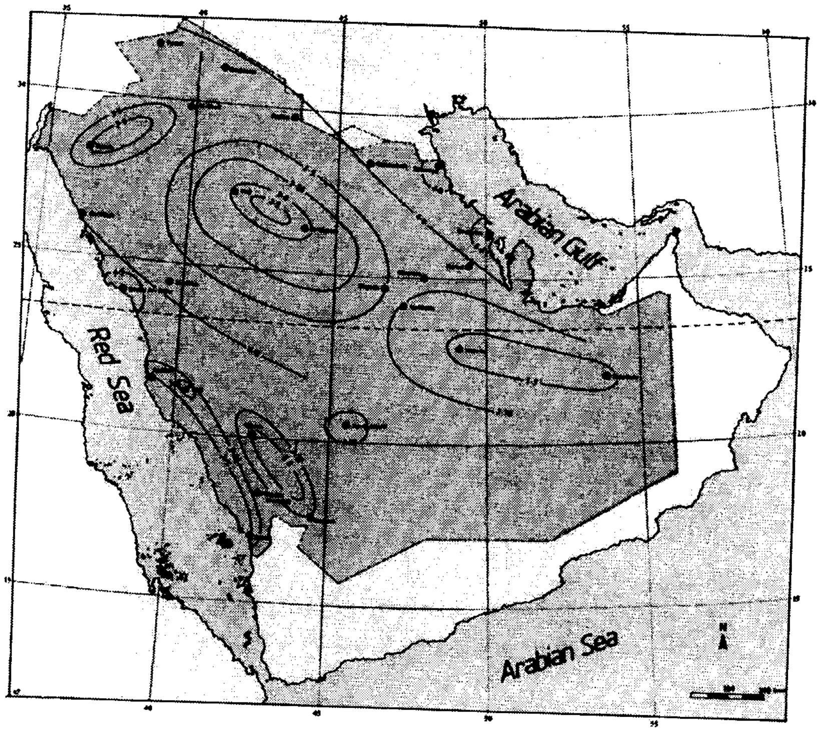


Figure IX. Annual mean wind speeds in Saudi Arabia (m/s)



4. *Syrian Arab Republic*

The Directorate of Research and Laboratories in the Syrian Ministry of Electricity published an overall assessment of the country's wind potential in 1984. The assessment was based on the data recorded by the Meteorological Services. In 1989, the *Syrian Wind Atlas* was published in cooperation with the Riso National Laboratory of Denmark. Wind stations are currently installed in Tiveuly, Syrian Arab Republic, for resource assessment.

In conclusion, it is clear from the preliminary data that the available wind data shown in table 5 below are not sufficient to accurately evaluate wind electricity potentials in almost all the ESCWA member countries; however, based on such data, wind electricity potentials for ESCWA member countries can be classified into three groups:

TABLE 5. RANGE OF ANNUAL WIND SPEED AT WINDY SITES IN ESCWA MEMBER COUNTRIES*

Country	Wind speed m/s
Bahrain	5-6
Egypt	4-10
Iraq	-
Jordan	5.5-7.5
Kuwait	5-6.5
Lebanon	3-5
Oman	4-6
Palestine	3-5
Qatar	5-7
Saudi Arabia	2.5–4.5
Syrian Arab Republic	4.5-11
United Arab Emirates	3.5-4.5
Yemen	4-6.6

* Data are taken from national reports and concerned authorities.

(a) ESCWA member countries with limited or no potential for wind electricity generation: Lebanon, Palestine, Saudi Arabia and the United Arab Emirates;

(b) ESCWA member countries with moderate potential for wind electricity generation: Bahrain, Kuwait, Oman, Qatar and Yemen;

(c) ESCWA member countries with promising potential for wind electricity generation: Egypt, Jordan and the Syrian Arab Republic (Golan Heights).

It should be noted that appropriate and accurate assessment may identify a specific site that could be classified in a different group than that shown above.

C. CRITERIA FOR EVALUATING WIND ELECTRICITY POTENTIALS

The potential for wind energy utilization for electricity generation depends on several factors but with a basic need for good wind resource sites. The following six categories can be used for evaluation of such potential in a specific ESCWA member country.

1. *The available wind resources*

A site for wind energy utilization for electricity generation should enjoy at least 400 watts per square metre at a height of 30.0 metres (i.e., wind density class 4 and 5), where wind speeds would vary between 4.6 and 6.0 m/s at a height of 10.0 metres or 7.0 - 7.5 at a height of 50 metres. In addition, the general electric energy would also depend on the annual wind frequency distribution which in turn will determine the availability of wind turbines.

2. *Energy strategies and policies*

The possible implementation of wind energy electricity projects are highly linked to the national energy policies that would or would not encourage wind energy utilization and adopt measures for its development and integration into the local/national electric grids.

3. *The possible wind penetration*

The capacity and characteristics of the electric would determine the possible permissible wind penetration rates defining the maximum wind capacity. Recent studies have indicated that the penetration can be a realistic assumption.

4. *Prospective site conditions*

The prospective site areas that can be used for wind generation do not account for all areas wherein utilizable wind speeds are available. The appropriate location of a wind turbine would require the turbines to be distanced from each other depending on the wind turbine capacity and the tower height. It is expected that turbine sizes will be up to 1,200 kW by 2005 and a 1,500 kW option will be available. In addition, the prospective sites are also dependent on the distance from the ground and land availability. Several intensive studies in the United States and Europe have evaluated effective windy site areas.

5. *Available local capabilities*

The potentials and costs of wind energy projects will depend on the percentage of local contribution in manufacturing wind turbines, site preparation, installation and operation.

6. *Financial availability*

The rate of implementing wind electric systems will naturally depend upon the availability of financial resources and appropriate financial mechanisms.

D. CURRENT DEVELOPMENT STATUS AND CONSTRAINTS

During the last two decades, several research institutions in the ESCWA region have carried out R&D and demonstration projects for wind electricity generation. The wind electric systems have been demonstrated, tested and evaluated in Egypt, Jordan, the Syrian Arab Republic and Yemen. The following is a brief on the status of development in these ESCWA member countries.

1. *Egypt*

Egypt has achieved remarkable success in developing the utilization of its high wind resources and has crossed the phase of demonstration to large-scale field application.

Chapter IV of this report elaborates on the Egyptian wind energy programme for electricity generation, which represents a leading example in the region. By March 2001, the total wind capacity in operation reached more than 70.0 MW (63.0 MW at Zafarana, 5.0 MW at Hurghada, and 2.0 MW from different sites), partially based on locally manufactured equipment.

2. *Jordan*

Wind-powered electricity generation systems were demonstrated by the RSS and the Ministry of Energy and Mineral Resources in Jurf al-Daraweesh, al-Ibrahimia and Hofa. One is a hybrid system incorporating a 10-kilowatt peak (kWp) photovoltaic (PV) unit and is used for village electrification. The project in al-Ibrahimia, where the wind speed averages 6.5 m/s, uses turbines totalling 320 kW 4x80 kW at a height of 25 metres and produces about 750 MWh of electricity annually, with about a 26 per cent capacity factor and a 96 per cent availability.

The first grid-connected wind energy demonstration plant was installed in Jordan in April 1988 at the site of al-Ibrahimia. Al-Ibrahimia wind farm consists of four Danish wind turbines each rated 80 kW and each has a rotor diameter of 17 metres and a hub height of 24 metres. The turbines are stall-regulated and rated power reaches approximately 14 m/s. Annual wind farm energy production is about 0.75 million kWh and the average capacity factor is 26 per cent. The annual mean wind speed is about 6.5 m/s.

Hofa wind farm consists of five 225 kW turbines that have been in operation since October 1996. The average annual energy production is about 2.5 million kWh and the capacity factor is about 26 per cent.

Moreover, in 1992, the RSS in cooperation with local industries has successfully completed the manufacturing and installation of the first generation of grid-connected wind turbines. The machine is pitch-regulated via a retrofitted German-made electrohydraulic control system. The blades are locally made from fibreglass and reinforced plastic (FRP) material. The turbine was tested on the grid and (as a prototype) showed an excellent performance with maximum power coefficient: $Cp_{max} = 33\%$ at tip - speed ratio = 5.

As well, wind battery charges for providing small quantities of electrical energy in remote areas for a variety of end-users. It is possible to make up system ratings from 500-1,000 watts centred around easily available automotive alternators. A fibreglass fabrication technique has been developed to manufacture blades to suit varied wind regimes and load requirements. Also, the RSS established in the late 1980s a facility for testing electric wind-pumping systems.

The technology of the “electrical wind-pumping system”, where the windmills generate electricity to the submersible pumps, was demonstrated in two sites (see table 6).

TABLE 6. PILOT ELECTRICAL WIND-PUMPING SYSTEM IN JORDAN

Location	Diameter (m)	Rated power (kW)	Total pumping head (m)	Yearly pumped water (m^3)	Energy output (MWh)
Jurf el-Daraweesh		14	65	>30000	> 31
Tal Hassan	2x15	2x20	75	50000	> 88

Since mid-year 2000, the Ministry of Energy and Mineral Resources of Jordan has been developing a programme for wind electricity utilization. In early 2001, the Ministry issued a tender for three wind farms with a 30 MW capacity apiece. A programme for supporting the Ministry to build national capacity in the field is being developed through the ESCWA Renewable Energy Promotion Mechanism (REPM).

3. *The Syrian Arab Republic*

The Ministry of Electricity in the Syrian Arab Republic installed a hybrid solar wind-powered system in Edra, north-east of Damascus, in 1979. The 2-kWp system comprises 24-volt solar PV panels and a 1 kW wind turbine.

The wind turbine has a horizontal-axis two-blade rotor. This system is the first hybrid solar/wind system in the ESCWA region. Unfortunately, the system is not equipped with measuring instruments for monitoring, and its output power is not currently utilized. At present, the system is not operating. One of the problems is the shortage of manpower; another is the lack of a fresh water supply.

The Syrian Ministry of Electricity, within the framework of a UNDP-financed project, installed a 150 kW wind energy conversion system driven by a three-blade wind turbine in the village of Ba'ath in the al-Quneiterah Governorate. The system is interconnected with the national grid and is operating successfully.

4. *Yemen*

As a pilot experiment, the Public Electricity Corporation in Yemen, in cooperation with DANIDA, installed an 8-kW wind-energy conversion system in December 1979—the first such system set up for electric power generation in the ESCWA region. The system was rated for a wind speed of 10.3 m/s. The plant experienced some mechanical difficulties, which were not completely overcome, and eventually the system was dismantled.

E. PROSPECTS FOR WIND ELECTRICITY DEVELOPMENT IN THE ESCWA REGION

As explained in part "A" of this chapter, with the exception Egypt, Jordan and the Golan Heights in the Syrian Arab Republic, the preliminary resources data do not show promising potentials for wind electricity generation in most of the ESCWA member countries. This emphasizes the need for conducting appropriate and accurate assessment in order to evaluate practical wind energy potential. However, the following highlight the current Egyptian potential and plans as well as the estimation potential in Jordan and the Syrian Arab Republic.

1. *Egypt*

Theoretical potentials for wind electricity generation in the Gulf of Suez was estimated to be 20,000 MW, while the official development programme estimated a total of 600 MW in the year 2010 as given by chapter VI of this report.

2. *Jordan*

The Jordanian National Energy Research Center has estimated the potential for wind resource to be more than 1,000 MW (12).

3. *The Syrian Arab Republic*

Apart from the "6X600 kW" wind farm installed at the Golan Heights site, any further evaluation of the wind electricity generation potentials should be based on appropriate resource assessment, which is not currently available.

IV. EGYPT'S WIND ENERGY PROGRAMME, DEVELOPMENT STATUS AND LESSONS LEARNED

A. BACKGROUND

Since the early 1980s, the Egyptian Government has embarked on a policy to promote a more widespread use of renewable energy in the country with a strategic objective that renewable energy has to contribute over 3 per cent of the electric demand by 2010, in addition to other non-electric applications. In this content, the development of the wind energy for electricity generation is a top priority in the near to medium term, targeting the installation of 600 MW by the year 2010.

In implementation of the strategic objectives, the New and Renewable Energy Authority (NREA) has developed and implemented a multi-phase programme for the development of wind electricity systems. The rationale and the procedure followed for the programme implementation are explained further hereinafter.

1. *The rationale*

The wind programme of Egypt was motivated by the need to develop an appropriate mix of energy resources, to create productive employment opportunities and to gain environmental benefits. The programme core objective was to develop large-scale exploitation of wind energy resources based on local manufacturing. In addition, the programme was based on the following:

(a) The Gulf of Suez has excellent exploitable wind resources;

(b) The Egyptian Power System, with more than 10 GW having been installed in the early 1990s and over 14 MW in 2000, and with continued growth demand, is large enough to absorb sufficient wind power capacity to merit the cost of development of a national capacity for wind turbine manufacturing;

(c) The considerable installed hydropower in Egypt makes it possible for the proven system to react to the fluctuations in wind power output without the need for spinning capacity.

2. *The programme development procedure*

The development of wind energy in Egypt has followed a logical procedure targeting gradual implementation while upgrading national capacities in the field and achieving the strategic targets, which include:

(a) Development of an appropriate resource assessment capacity and precious evaluation of the wind resources in gradual sequence phases;

(b) Demonstration of wind electricity potential and upgrade relevant national expertise;

(c) Build a national wind turbine manufacturing capacity in Egypt;

(d) Develop the required institutional capacities for planning, installation, operation and maintenance.

B. THE EXPERIENCE OF WIND RESOURCES ASSESSMENT

Given the importance of the appropriate wind resource assessment for the evaluation of wind energy potentials, concerted efforts were devoted in Egypt for resource assessments in preliminary wind mapping (1986) and the development of the Gulf of Suez atlas (1995) and the wind atlas of Egypt.

1. *Preliminary wind map, 1986*

Preliminary investigations based on the data obtained from the national meteorological stations led to the development of the preliminary wind map in 1986. Its use was limited to identifying only those regions that were promising. In order for this data to have any real value, the promising regions need to be investigated more thoroughly for verification and for more precise wind resource assessment using special devices and methodologies (18).

2. *Wind atlas for the Gulf of Suez (1991-1995)*

In 1990, the NREA issued the *Wind Atlas of the Gulf of Suez* based on detailed measurements and advanced analysis methodologies. The *Wind Atlas* proved the existence of a widespread and high-wind energy resource along the Gulf of Suez with mean wind speeds and energy densities of 8-12 m/s and 500-1,400 watts/m^2, estimated at a height of 25 metres over roughness class 0 (water) (15). Annex I is a brief on the assessment of wind energy resources in Egypt with some illustrative examples.

3. *Wind atlas for Egypt*

This is an ongoing project that started in 1998 and will end in 2003. The objective is to improve the conditions for efficient and environmentally sustainable realization of the Government plans for future development of wind energy in Egypt. It consists of two phases as follows:

(a) *Phase 1 includes*:

(i) Elaboration of an extended wind atlas for the Gulf of Suez, including meteorological measurements, micro-and meso-scale modelling, and satellite imagery;

(ii) Plans to create an ornithological atlas for wind energy planning;

(iii) Reports with recommendations for future wind farm planning and related environmental assessment.

(b) *Phase 2 includes*:

Plans to create a wind atlas for Egypt, including additional meteorological measurements, micro- and meso-scale modelling, and satellite imagery for selected regions;

In conclusion, the Egyptian experience in wind resource assessment emphasizes the essential need for an appropriate, well-planned and instrumental assessment process, without which the evaluation of wind potentials or sites cannot be effective.

C. THE CURRENT STATUS AND FUTURE PLANS

In the mid-1980s, the concerned Egyptian Authorities were in a position to take a decision for an overlapped plan leading to the implementation of pilot and demonstration projects parallelling the efforts of ever-increasing precision of wind resource assessment results, with the feedback coming from the performance evaluation of the projects to benefit the verification and rectification of those results.

Encouraged by the high wind regime at the Red Sea, the first steps taken to exploit wind energy were started by limited pilot projects followed by a plan for large-scale wind energy development. The activities and main achievements can be summarized as follows:

1. *Pilot and demonstration projects*

(a) *The first wind farm with a capacity of 400 kW* was installed in 1988 in Ras Ghareb on the Red Sea Coast serving one of the oil companies. The wind farm consists of four 100 kW units. Fully imported wind turbines were used;

This pilot plant was used for the first field information and wind turbine performance determinant under the Egyptian conditions, as well as for evaluating the possibility of manufacturing, which was effectively started as a consequence of those results.

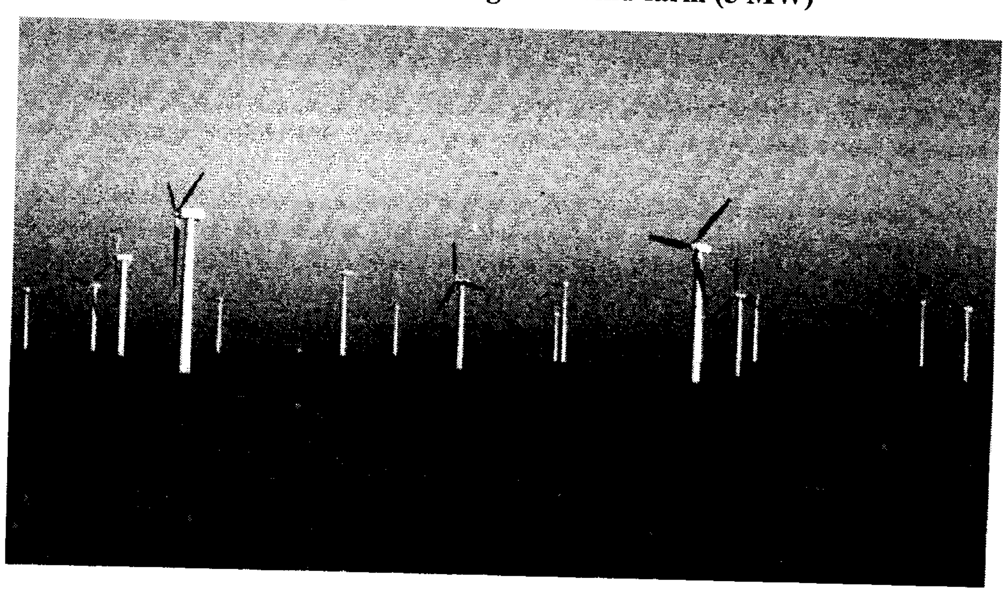
(b) *The second wind farm consists of four 100 kW units* that were installed in 1992 at Hurghada on the Red Sea Coast; 45 per cent of the wind turbine components were locally manufactured, mainly blades, towers and other mechanical parts. The farm has been connected to the local network of Hurghada City. In 1998, the network was connected to the national grid. This wind-generated electricity is powering desalination units to produce 130 m^3/day of potable water to satisfy the water needs at the NREA's site facility at Hurghada;

(c) *A grid-connected 5 MW wind farm at Hurghada*, shown in figure X, consists of 38 wind turbines of different technologies (pitch-regulated/stall-regulated blades and tubular/lattice towers) and ratings (from 100-300 kW); 50 percent of the components are locally manufactured. The farm has been connected to the local grid and has operated successfully since 1993, producing about 10 million kWh/year.

This project, together with the Wind Energy Technology Center (WETC) that exists on the same site, forms the real opportunity that allowed the national manpower involved in dealing with the different designs of windmills—whether in the erection, operation and maintenance and applied researches—for comparative performance evaluation in order to generate an adequate group of national crew members comprised of technicians, engineers, planners and researchers who are deeply motivated to acquire acquaintance with the up-to-date international technological development in the field.

This well-trained manpower forms the driving force for the realization of the ambitious long-term Egyptian programme as planned with a high level of reliability and confidence in achieving success.

Figure X. A part of Hurghada wind farm (5 MW)



2. *Technology transfer and local manufacturing*

In support of the policy of the Egyptian Government to localize renewable energy technologies and encourage technology transfer, a serious programme for the local manufacture of wind turbines was undertaken in 1998. The programme was initiated in cooperation with UNDP and the United Nations Industrial Development Organization (UNIDO). An assessment of local manufacturing capabilities was carried out and Egyptian counterparts were selected. Two joint ventures were established for the manufacture of blades and towers. The locally produced components were used at the demonstration wind farm in Hurghada for turbines with capacities of 100 to 300 kW apiece. It should be noted that the large-scale Zafarana wind farm project will depend increasingly on locally made wind energy components, and producers are preparing themselves for this eventually; the number of Egyptian firms manufacturing the needed items is increasing gradually with the implementation of the programme. Among the firms currently involved in wind turbine manufacturing are the Egyptian Iron and Steel Company, the Suez Canal Shipyard, Icon, and the Arab Organization for Industrialization. The contribution of local manufacturers is currently around 45 per cent in terms of turbine value, but this figure is expected to reach 70 per cent.

3. *Large-scale wind energy development plans*

In 1994, the NREA developed a programme for Bulk Renewable Energy Electricity Production Projects (BREEPP) with wind components in implementation.

An area of 80 km^2 on the Gulf of Suez at the Zafarana site has been allocated for the NREA to start implementing the large-scale wind electricity programmes. Current status of programme implementation includes:

(a) *Operating projects*

On 22 March 2001, the first large-scale wind farm of 63 MW capacity was inaugurated and included the following:

(i) The first phase (30 MW) of a 60-MW wind farm, in cooperation with DANIDA, has been connected to the national grid and has been in operation since November 2000. This phase produces electric energy totalling about 120 GWh/year;

(ii) The first phase (33 MW) of an 85-MW wind farm, in cooperation with the German government, has been connected to the national grid and has been in operation since February 2001. The annual electric energy production is about 130 GWh/year.

(b) *Projects under implementation*

The second phase (30 MW) of a 60-MW wind farm in cooperation with DANIDA is under implementation.

(c) *Projects under preparation*

(i) The other two stages (26 MW each) of an 85-MW wind farm, in cooperation with the German government (to be operative by 2002 and 2003 respectively), are under preparation;

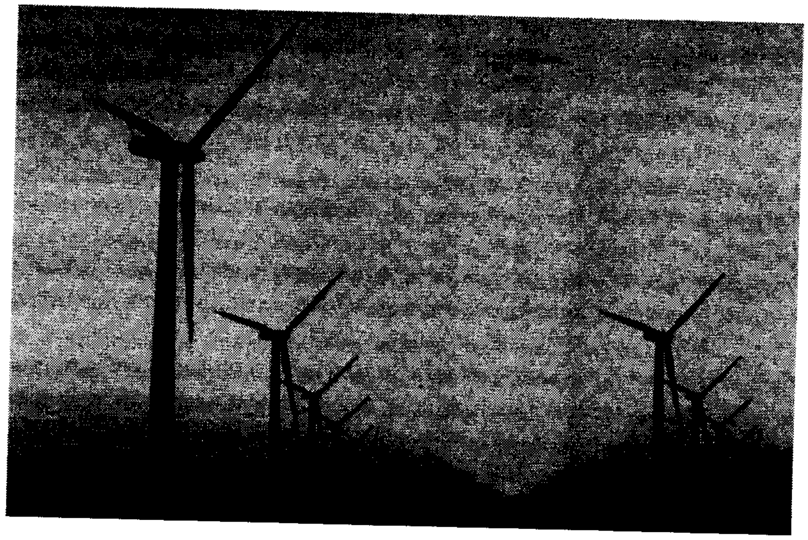
(ii) The two wind farms described in (b) and (c) above are expected to be completed during the year 2002, and the total operating capacity is expected to reach 145 MW.

(d) *Projects under negotiations*

(i) A 120-MW wind farm project at Zafarana (in two stages), in cooperation with Japan, is in the negotiating phase, while a feasibility study was performed for the project (see figure XI);

(ii) A 60-MW wind farm at Zafarana, in cooperation with Spain, is under negotiations. A memorandum of understanding was signed with the selected Spanish consulting firm that was assigned to perform the consulting services for the project. A tender document has been prepared during the year 2000, in parallel with continued negotiations with the concerned Spanish authorities for allocating an appropriate financial package to implement the project.

Figure XI. A part of Zafarana wind farm



The following shows the effect of appropriate wind resource data on the productivity at Zafarana wind farm (see table 7):

A network of modern wind measuring masts/classifiers/monitoring stations were installed at key locations within the promising areas. The measurements were taken at different heights and analysed, not only to calculate accurately the average annual wind speeds, but also to identify other wind regime characteristics, such as frequency, distribution and effective wind availability between the cut-in and cut-off speeds of the wind turbines (minimum and maximum allowable speeds to operate a wind turbine without succeeding active power from the network in case of less than minimum wind speed or unsafe operation at more than maximum wind speed), in addition to other several important characteristics.

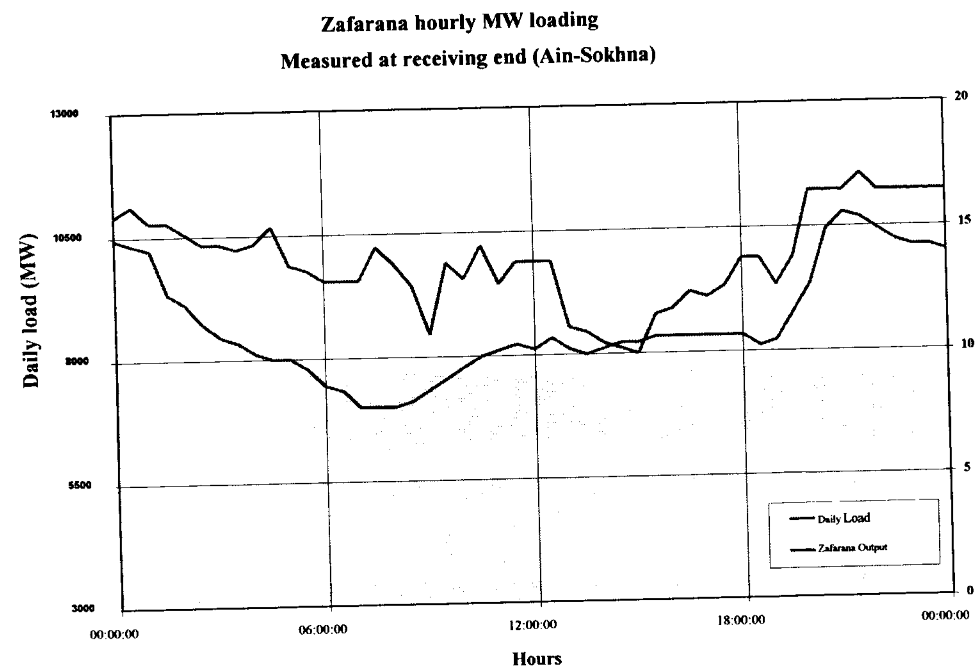
TABLE 7. THE AVAILABILITY OF EFFECTIVE WIND SPEEDS AT ZAFARANA

	Hub height			
Range	600 kW (43 m)	660 kW (45 m)	1000 kW (50 m)	1000 kW (60 m)
0-3.5 m/s	5.1%	5%	4.7%	4.4%
3.5-13 m/s	74.8%	74.1%	72.6	68.2
0-4 m/s	6.5%	6.3%	6.1%	5.6%
4-13 m/s	73.4%	72.8%	71.2%	67%
0-4.5 m/s	8.1%	8%	7.6%	7.1%
4.5-13 m/s	71.8	71.1	69.5	65.5
13-25 m/s	20.1	20.9	22.7	27.4
More than 25 m/s	0%	0%	0%	0%
Average wind speed m/s	9.9	10	10.2	10.5
Annual energy production MWh/year (100 % availability)	3 023	3 526	5 099	5 353

Availability of effective wind speeds at 43 m (in case of 3.5 m/s cut in speed) = 94.9 %
Availability of effective wind speeds at 43 m (in case of 4 m/s cut in speed) = 93.5 %
Availability of effective wind speeds at 43 m (in case of 4.5 m/s cut in speed) = 91.9 %

Figure XII shows the average daily wind electricity power generated in comparison with the national grid local profile with a marketable wind contribution in the daily peak period.

Figure XII. Comparison between generation electricity profile and load at Zafarana



4. *The future plans*

The aim of the programme is to accumulate a total installed capacity of 600 MW at the wind farm, 300 MW of which will be undertaken by the private sector based on the BOOT (build-own-operate-transfer) system by the year 2010. The annual electric energy production will be increased to about 2.5 billion kWh, corresponding to a fuel savings of 0.5 tons of oil equivalent per year (TOE/y).

TABLE 8. WIND FARMS: PLANNED INSTALLED CAPACITIES AND ELECTRIC ENERGY GENERATION

Five-year development plans	Installed capacity (MW)			Cumulative capacity (MW)	Energy generation (annual energy at the end of the period) TWh/year
	Red Sea	East of Oweinat	Total capacity		
1997-2002	120	—	120	120	0.48
2002-2007	330	—	330	450	1.8
2007-2010	100	50	150	600	2.4

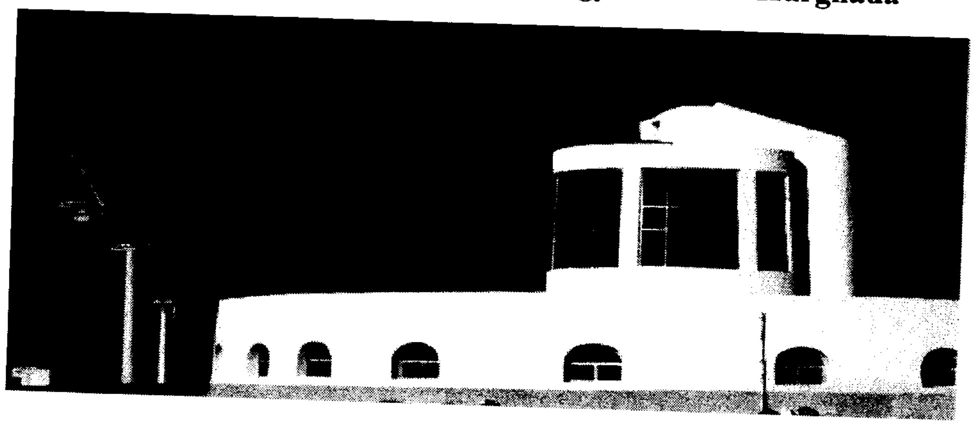
5. *Wind Energy Technology Center*

To support national wind energy programmes and upgrade the local capabilities in the field, the Wind Energy Technology Center in Hurghada was established in cooperation with Denmark. It includes a mechanical and electrical workshop and a training centre. The main activities of the WETC are:

(a) Research and development;
(b) Testing and certification for wind turbine components;
(c) Technical evaluation;
(d) Training programmes.

The WETC can serve local objectives and regional cooperation programmes.

Figure XIII. Wind Energy Technology Center at Hurghada



D. Lessons learned

The experience gained through the planning, development and implementation of the Egyptian wind programme identifies several essential milestones for a successful programme in the field of renewable energy in general and wind energy in particular. They include:

1. *The need for an appropriate wind resource assessment*

As it has been discussed earlier, the site selection for a wind energy project depends mainly on the availability of appropriate wind regimes on site, which in turn critically affects the evaluation of the possible level of electric energy generation. It is owing to these facts that wind resource assessment should:

(a) Follow gradual identification of potential area zones within the country and concentrate most on promising sites among these for accurate resource assessment;

(b) Resource assessment at identified area zones should include all parameters, the consideration of effective issues and the specification and accuracy of equipment as described in annex I of this report.

2. *Upgrading of relevant national capabilities*

The programme should be develop in phases that are identified appropriately to enhance the learning processes and national capacity-building needs to maximize the local contribution to the processes in order to reduce costs, create job opportunities and sustain performance. This would include:

(a) Performing resource assessment and updating it;

(b) Local manufacture of wind system components, utilizing available industrial capacities with minimum additions;

(c) Utilization of available local expertise siting installation, operation and maintenance;

(d) Integration of wind farms into local/national electric grids.

3. *Integrating wind plans with the overall electricity planning process*

The plan for wind energy electricity generation should be managed and evaluated as an integral part of the overall power sector plan.

It goes without saying that the in-depth experiences gained on all the spectrum of activities and practices regarding the planning and implementation of wind electricity projects are quite available and cannot be expressed in such a brief report.

In addition, the NREA is ready for cooperation with its sister Arab organizations for exchanging such experiences.

PART TWO

BIOMASS ELECTRICITY GENERATION

V. BIOMASS RESOURCES AND TECHNOLOGIES

Biomass resources—particularly agricultural residues and animal wastes—have been traditionally used in developing countries by direct combustion for domestic cooking and heating. Meanwhile, most biomass in industrialized countries is converted into electricity and process heat in cogeneration systems (combined heat and power [CHP]) at industrial sites or at municipal district heating facilities. In the last two decades, technologies for electricity generation using biomass were successfully developed using different biomass resources, including agricultural, domestic, municipal and industrial waste resources, as well as energy plantation.

This chapter overviews the biomass resources, classification, and its global potentials. It also describes the available technologies for biomass-produced electricity, together with prospects for its development and application.

A. CLASSIFICATION OF BIOMASS RESOURCES

There are various ways of classifying biomass energy resources. One useful approach is to consider whether the resource is primarily established to produce energy from biomass (e.g. energy plantations) or whether the energy is produced as a secondary or incidental element, e.g. as part of a waste management process.

1. *Primary biomass resources*

The main primary biomass resources are crops that are specifically planted for energy production and are classified according to its energy-use technology.

(a) Crops grown for combustion or gasification to produce heat, to fuel a power station, or both;
(b) Crops grown for the production of liquid fuels, mainly for vehicles, e.g. bio-diesel or ethanol.

Growing crops specifically for energy has significant potential, however, land use for bio-energy could intensify competition with other important land uses, especially food production, which can be minimized if degraded lands are targeted for energy. Meanwhile, a wide variety of technical, socio-economic, and other challenges are involved in successfully growing energy crops on degraded lands, but the many successful plantations already established on such land in developing countries demonstrate that these challenges can be overcome.

Energy crops can be produced in two ways: (1) by devoting an area exclusively to production of such crops (energy plantations); or (2) by co-mingling the production of energy and non-energy crops. Since energy crops typically require several years of growth before the first harvest, co-production in some form has the benefit of providing an energy-crop. The co-production approach also helps to meet environmental and socio-economic criteria for land use.

2. *Secondary biomass resources*

Secondary biomass resources, which are produced as a by-product of plantation residues, animal manures, sewage, and so on, include:

(a) Forestry residues for combustion to provide energy on site, either as heat, power or both;

(b) Agricultural residues such as straw or poultry litter for use as a boiler fuel, sometimes in power stations;

(c) Sewage sludge, domestic waste (municipal solid waste [MSW]) and other organic residues for digestion or fermentation to produce fuel gas or liquid fuels.

Global production of biomass residues, including by-products of food, fibre and forest production, exceeds (110 EJ/year), perhaps 10 per cent of which is used for energy. Residues concentrated at industrial sites (e.g., sugarcane bagasse) are currently the largest commercially used biomass source. Biomass residues might play an important role in the densely populated regions, where much of the land is used for food production and can generate large quantities of by-product residues. The domestic sector of the densely populated regions also produces large quantities of MSW.

Some residues cannot be used for energy in some cases, where the collection and transport costs are prohibitive; in other cases, agronomic considerations dictate that residues be recycled to the land. Still, in other cases, there are competing non-energy uses for residues (such as fodder, construction material, industrial feedstock, and so on).

B. BIOMASS TECHNOLOGIES FOR ELECTRICITY GENERATION

Biomass energy has the potential to be "modernized" worldwide, i.e., produced and converted efficiently and cost-competitively into more convenient forms such as gases, liquids, or electricity. There are a variety of technologies that can convert solid biomass into clean, convenient energy carriers. Most of these technologies are commercially available today although some more than others. If widely implemented, such technologies would enable biomass energy to play a much more significant role in the future than it does today, especially in developing countries. Energy services derived from biomass results in much cleaner and more efficient use of available biomass resources than traditional uses of bio-energy in developing countries.

This part of the report describes the state-of-the-art technologies currently available for producing electricity from biomass, where there are three primary routes in which biomass can be converted into electricity.

The first is to burn the biomass from different resources using different combustion systems (conventional or improved fluidized bed) and use the heat to generate steam, which drives a conventional steam turbine to produce electricity. This is the method that has been most widely used.

The second approach is to gasify the biomass (gasification), generating a combustible gas which can then be burned, either in a boiler to generate steam or in a gas turbine or piston engine. The capital cost of the gasification route appears to be lower than the cost for a conventional steam-generating plant.

The third approach is to ferment the biomass (anaerobic digestion) to generate gases or liquid fuel. This can then be burnt in a boiler, engine or gas turbine to generate power. However, the primary attraction of fermentation is that it produces a fuel that can be used to power cars and trucks. For power generation, it may not offer the optimum route.

In addition, fuel cells are the most modern technology for producing electricity. However, it still needs more investigation to be field applicable and competitive.

1. *Direct combustion, combined heat and power*

Biomass can be directly burnt in a boiler through which pipes carry water that is heated to generate steam. The steam is then used to drive a steam turbine, which turns a generator and produces electricity.

(a) *The technology*

The predominant mature and commercial technology for generating megawatt (MW) levels of electricity from biomass is the steam-Rankine cycle. Most steam cycle plants are located at industrial sites, where the waste heat from the steam turbine is recovered and used for meeting industrial-process heat needs. Such combined heat and power (CHP), or co-generation systems, provide greater levels of energy services per unit of biomass consumed than systems that generate power only. Figures XIV and

XV show schematic diagrams for two biomass-fired CHP systems using: (i) a back-pressure steam turbine; and (ii) a condensing-extraction steam turbine used in the case that industrial processes heat is needed. A purely condensing steam turbine is generally employed where there is no demand for process heat to maximize electricity production (Figure XVI). It is to be noted that drying of the biomass is not usually required before combustion, but will improve overall efficiency if waste heat is utilized for drying.

In the USA, the installed biomass-electric generating capacity exceeds 8,000 MW, with the majority of this capacity located at pulp and paper mills, where biomass fuels are available as by-products of processing. A significant number of biomass power plants are also found in Scandinavia, especially Sweden, however, there is relatively little capacity installed in developing countries, most of it is located at factories making sugar and/or ethanol from sugarcane, where the steam-Rankine CHP system is fueled by bagasse, the fibre residue of sugarcane.

The steam-Rankine cycle uses different boiler designs, depending on the scale of the facility and the characteristics of the fuel being used. The initial pressure and temperature of the steam, together with the pressure to which it is expanded, determine the amount of electricity that can be generated per kilogram of steam. Biomass-fired steam-Rankine plants operate with far more modest steam conditions than are used in large, modern electric-utility coal-fired steam-Rankine systems. It can also use fluidized-bed combustion, wherein the combustion air enters as jets from below to "fluidize" the burning biomass fuel particles and the sand that make up the bed. The commercial introduction of fluidized-bed technologies started in the late 1970s/early 1980s. All these boilers have the capability to burn different fuels or mixtures of fuels. The best biomass plants today have total efficiencies of 20 to 25 per cent.

Low efficiencies, together with relatively high capital costs, explain the reliance of existing biomass power plants on low-, zero-, or negative-cost biomass. Many regions of the world still have significant untapped supplies of low-cost biomass feed stocks for which the economics of steam-Rankine systems are probably reasonable. Sugarcane processing industries present major opportunities for steam-Rankine-based CHP generation from biomass.

Table 9 summarizes the characteristics of a steam-Rankine cycle combined heat and power system.

(b) *The costs*

The costs of steam-Rankine systems vary widely depending on the type of turbine, the type of boiler, the pressure, the temperature of the steam, and other factors. An important characteristic of steam turbines and boilers is that their capital costs (per unit of capacity) are scale-sensitive (this is the main reason coal and nuclear steam-electric plants are built big—500 to 1,000 MWe). Moreover, biomass steam-Rankine systems are constrained to relatively small scales (because long-distance transport of biomass fuels is costly). As a result, biomass steam-Rankine systems generally are designed to reduce capital costs at the expense of efficiency. The capital costs/kWe is around US$ 2,000, and the generating cost is in the range of US$ 0.104/kWh, including about US$ 0.012 for biomass.

(c) *The environmental impact*

Biomass steam-Rankine systems pose a number of environmental issues, including the potential for particulate emissions released into the air. Flue-gas-filtration systems are required to minimize this problem. Ambient-temperature air or water is used to cool the condenser in biomass steam cycles. If the reservoir of water or air available for cooling is not sufficiently large enough, thermal pollution may result. Ash generated during combustion contains much of the inorganic minerals found in the original biomass. Ideally, the ash would be returned to the oil. In many cases, it is sent to a landfill.

TABLE 9. TECHNOLOGY SUMMARY: STEAM TURBINE COMBINED HEAT AND POWER (15)

Typical electrical capacity	1 to 50 MWe
Typical heat to power ratio[a/]	5
Technical parameters	
Typical steam conditions[b/]	20 to 80 bar; 400-500°C
Biomass fuels	Any/all (boiler design varies with fuel)
Typical biomass rate [c/]	1 to 2 dry kg/kWh; 6,575 to 13,150 dry tons/year per installed MWe
Technology availability	Boilers and turbines manufactured in most large developing countries
Key cost factors	Capital investment (especially at smaller scales), fuel cost
Technical concerns	Deposition on boiler tubes with high-ash biomass (with low ash softening temperature); Boiler feed-water purity (at minimum, demineralization and de-aeration are required)
Environmental and socio-economic parameters	
Environmental strengths	Efficient use of biomass with CHP; multi-fuel capability
Environmental issues	Particulate emissions, thermal pollution; as disposal
Total direct jobs	Two per MWe at 10 MWe; one per MWe at 30 MWe (California experience)

a/ This varies significantly with the amount of process steam produced. The number shown is typical for a back-pressure steam turbine. With a fully condensing steam turbine, no process heat is produced.

b/ Steam pressures can be as low as 20 bar, as is found at many sugar factories in developing countries, or as high as 100 or 120 bar, as is found at many large coal-fired thermal power plants.

c/ These figures assume an input biomass with a moisture content of 50 per cent and an energy content of 18 GJ per dry ton. Also, assumed overall conversion efficiencies to electricity are 10 per cent (which might be representative of a system using 20-bar steam in a back-pressure turbine) to 20 per cent (which might be representative of a system using a fully-condensing turbine with a steam pressure of 60 bar). For the biomass rate per MWe, a 75 per cent capacity factor is assumed, i.e., the annual electricity production per installed kWe is 6,575 kWh.

Figure XIV. Schematic diagram of a biomass-fired steam-Rankine cycle for combined heat and power production using a back-pressure steam turbine

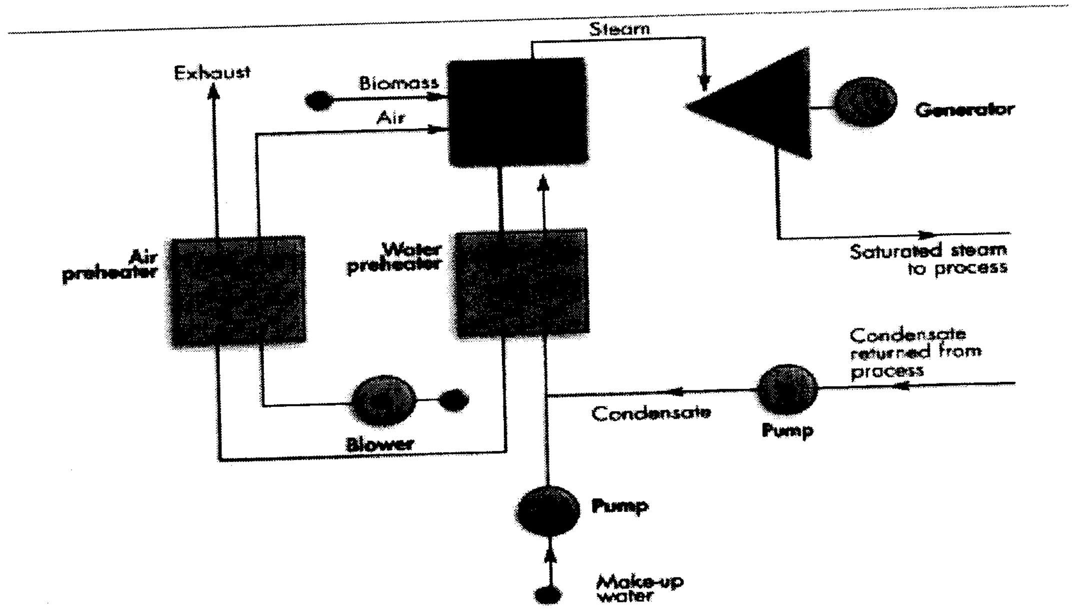


Figure XV. Schematic diagram of a biomass-fired steam-Rankine cycle for combined heat and

power production using a condensing-extraction steam turbine

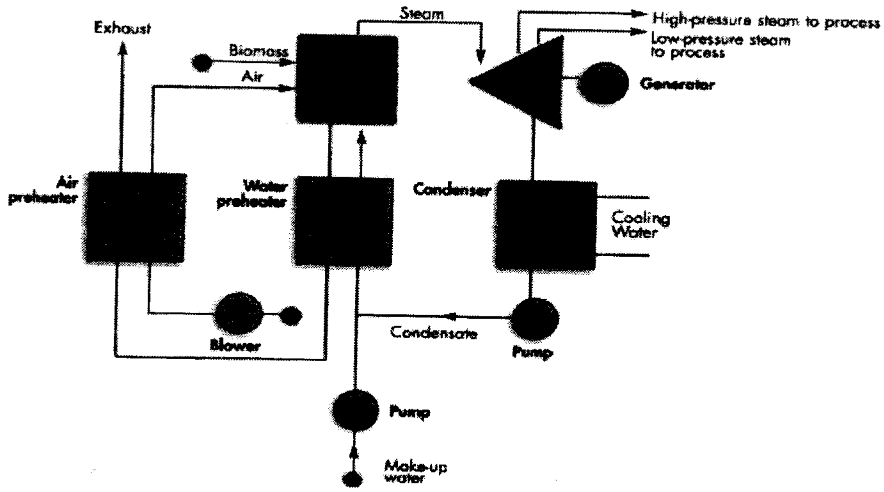
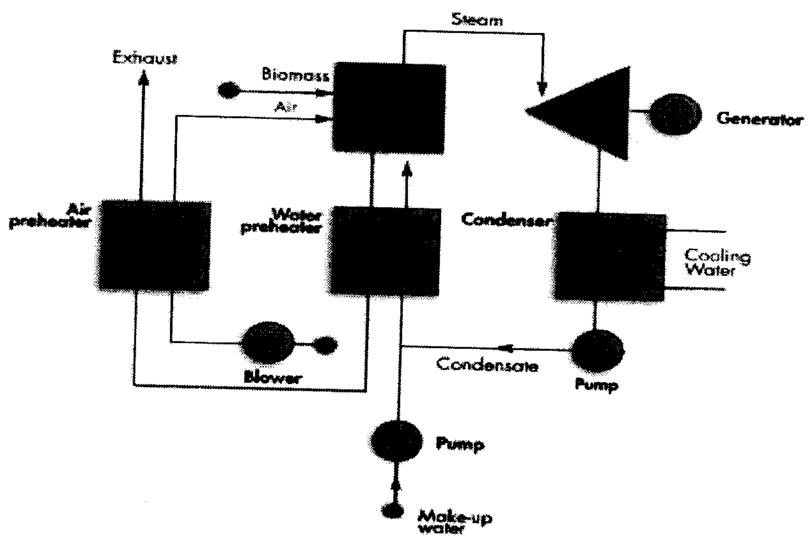


Figure XVI. Schematic diagram of a biomass-fired steam-Rankine cycle for dedicated power generation using a condensing-extraction steam turbine



Source: *Bioenergy Primer: Modernised Biomass Energy for Sustainable Development*,. UNDP, 2001.

2. *Biomass gasification*

(a) *The technology*

The term gasification commonly refers to high temperature conversion of biomass, where it is burned without sufficient air for full combustion, but with enough air to convert the solid biomass into gaseous fuel. The produced gas is mostly called producer gas and has a calorific value of around 14-15 per cent of that of natural gas (NG). It can then be used for electricity generation or shaft power.

There are two basic gasifier designs: updraft and down draft fixed bed gasifiers. The updraft gasifiers have high energy efficiencies, however, the product gases have unacceptably high concentrations of tars and oil which must be filtered. On the other hand, down draft fixed bed gasifiers produce significantly less tar and the gas cleaning can be done with acceptably small energy losses.

Producer gas can be used for electricity generation using steam or gas turbines; it can also be used for producing shaft power.

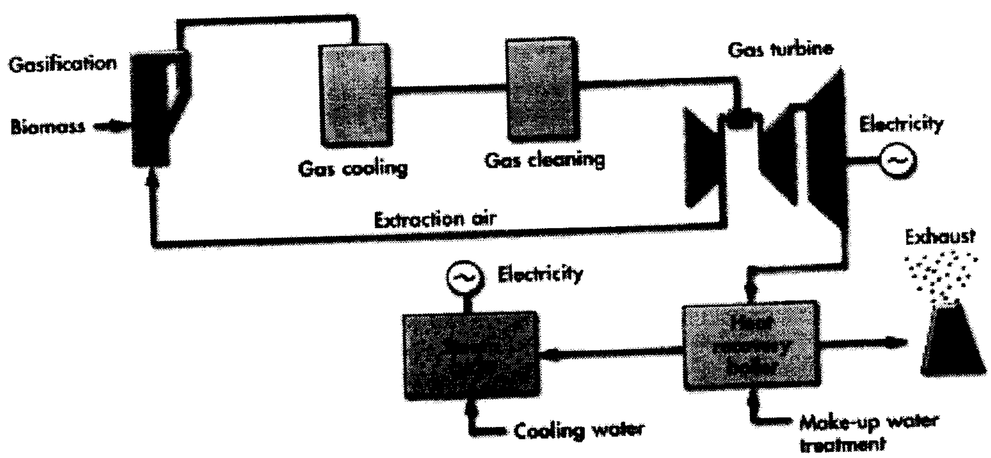
(i) *For electricity generation*

The producer gases can be burned in conventional boilers after suitable cleanup. The steam-Rankine cycle is the predominant commercial technology used today with biomass fuel in the 5- to 100-MW output range, however, producer gases are most efficiently used in gas turbines as a part of integrated gasification combined cycle (IGCC) systems for electricity generation. The efficiency of the system can be improved further by capturing heat from the gas turbine exhaust for generating steam to drive a steam turbine.

In approximate terms, the biomass-gasifier gas turbines (BIG/GT) technology shown in figure XVII will make electricity generation two or more times as efficient as the steam cycle, and the capital cost per installed kW for commercially mature BIG/GT units is expected to be lower than for comparably-sized steam cycles.

The overall economics of biomass-based power generation are expected to be considerably better with a BIG/GT system than with a steam-Rankine system, especially in situations where biomass fuel is relatively expensive. BIG/GT technology is expected to be commercially ready within a few years, based on the substantial demonstration and commercialization efforts ongoing worldwide today.

Figure XVII. Schematic diagram of one possible configuration of a biomass-gasifier/ gas turbine combined cycle



Source: *Bioenergy Primer: Modernised Biomass Energy for Sustainable Development*,, UNDP, 2001.

(ii) *For shaft power*

Producer gas can also be used to fuel internal combustion engines: either diesel or gasoline engines. However, the diesel engines are favoured owing to their higher efficiency, durability and reliability. Figure XVIII shows the basic layout of a biomass gasifier internal combustion engine system.

Table 10 summarizes the main characteristics of the biomass gasification technology for electricity generation and shaft power.

(b) *The cost*

The cost of producing electricity with a gasification-based system would vary widely based on the type of biomass, capital costs, as well as the cost of diesel fuel when used in a duel-fuel system.

(c) *The environmental impact*

At a biomass gasification facility, environmental emissions of potential concerns are primarily liquid effluents from the gas cleanup system. Tar-contaminated liquid effluent contains carcinogenic compounds, such as phenols, and thus require appropriate treatment before discharging into the environment.

Leakage of poisonous and odourless carbon monoxide at the conversion facility and at points of gas use (e.g. cooking stoves) is an additional danger. Other gaseous pollutant emissions are small in comparison to emissions from direct combustion of solid fuels. The solid residue from gasification of most biomass types is an inert inorganic material that has some by-product value, for example, as a mineral fertilizer or as a construction material (as in the case with rice husk ash).

TABLE 10. TECHNOLOGY SUMMARY: BIOMASS GASIFICATION

Energy services	Electricity (diesel)	Shaft power	Gas turbine/combined cycle
Range of output	5 to 500 kWe	5 to 500 kW	5 to 100 MWe
Range of biomass input	~5 to ~500 kg/hour		
Technical parameters			
Basic equipment	Gasifier, gas cleanup, diesel engine		Gas turbine, heat recovery boiler, steam boiler
Fuel inputs	Per kWh: 1-1.4 kg biomass + ~0.1 litre diesel (gives 60-70% diesel replacement)		0.5 to 0.67 dry kg per kWhe generated
Energy outputs	~ 1 kWh per (kg biomass + 0.1 litre diesel)		3288 to 4405 dry ton/year per MWe installed
Acceptable biomass	Wood chips, corn cobs, rice hulls, cotton stalks		
Biomass requirements	Sized (10-150 mm, depending on gasifier design)		
Useful by-products	Waste heat, mineral ash		
Key to good performance	Good gas cleanup (esp. tars), high capacity utilization		
Special safety concerns	Leakage of (poisonous) carbon monoxide, exposure to tar		
Technology availability	Available from several multinationals		
Difficulty of maintenance	Diesel engine maintenance		"Only demonstrated"
Key cost factors	Capital, diesel fuel, operating labour		Capital, fuel cost

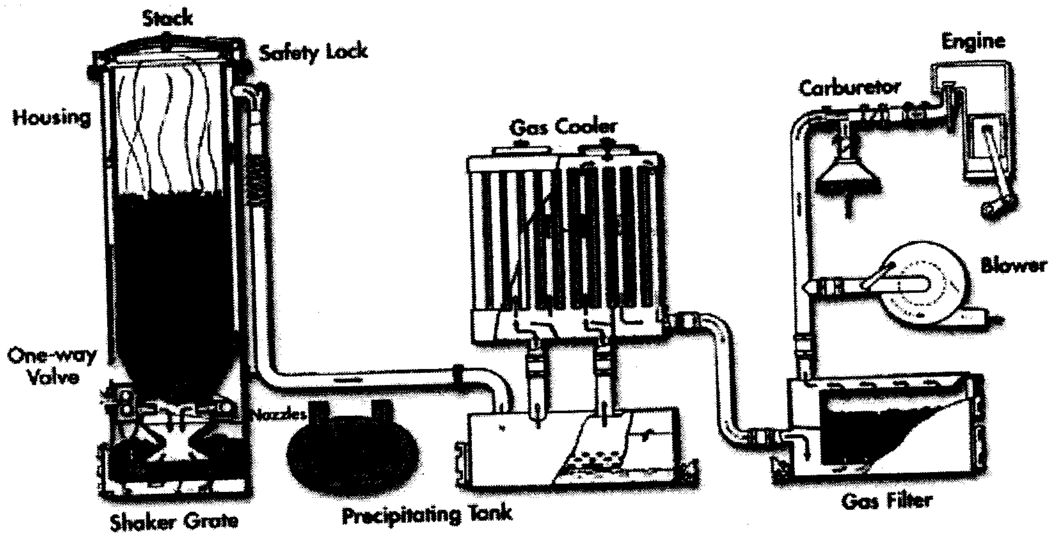
Source: Bioenergy Primer: Modernised Biomass Energy for Sustainable Development,, UNDP, 2001.

3. *Anaerobic digestion*

(a) *The technology*

The anaerobic digestion is a low-temperature biological waste treatment and end-energy conversion method, which can be applied to many different biomass-containing wastes of industrial, agricultural or domestic origin. Anaerobic digestion is used widely in sewage works as a means of both reducing sludge volumes and producing gas, referred to as biogas, containing 55-65 per cent methane. Biogas is used for supplying heat and can also be used for generating electricity by feeding it into a gas engine. Adopting the system to generate both heat and power is generally a cheap and cost-effective measure. Figure XIX shows the stages of biomass anaerobic digestion, while figure XX shows the man components of biogas systems.

Figure XVIII. Basic layout of a biomass gasifier internal combustion engine system



Source: *Bioenergy Primer: Modernised Biomass Energy for Sustainable Development,*, UNDP, 2001.

Figure XIX. The three stages of biomass anaerobic digestion

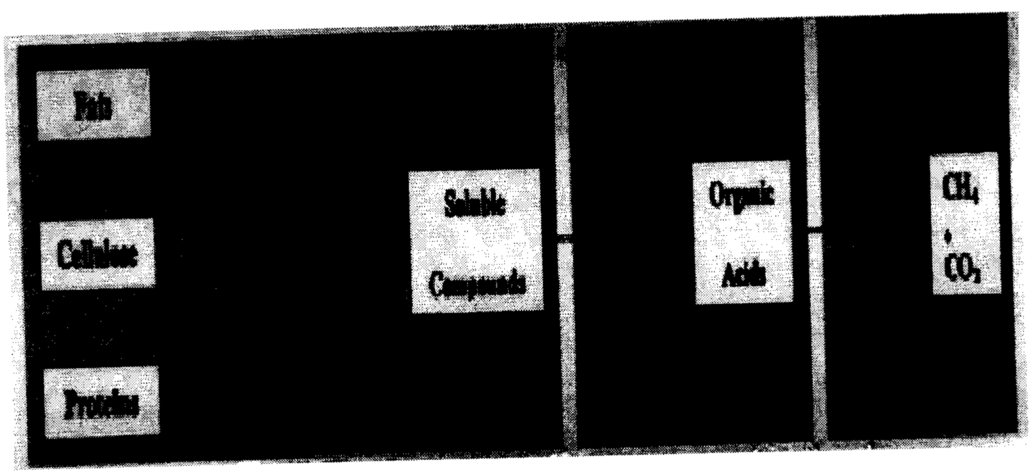
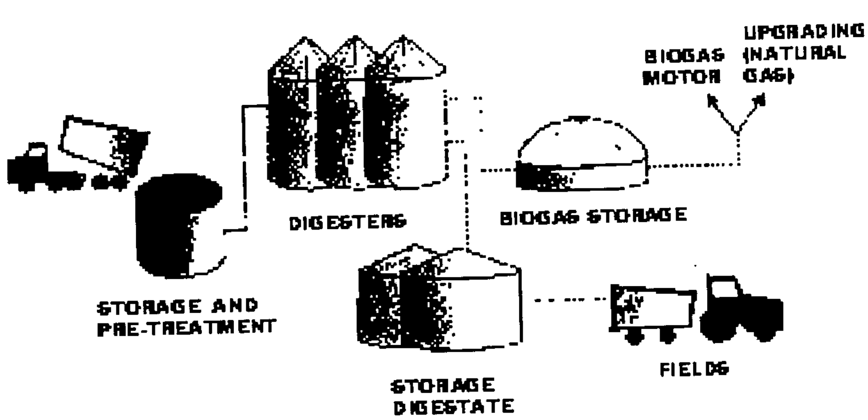


Figure XX. The biogas systems (plants) main components



Temperature control is crucial in anaerobic digestion. The optimum temperature is 35°C-37°C. Initially, the process may need some supplementary heating for starting, and then combustion of some of the produced biogas keeps the process running at a suitable temperature. The pH (hydrogen ion concentration) of the mixture is also critical as methanogenesis is only really effective around pH7. The presence of toxic materials may inhibit the process and there must be adequate supplies of nutrients, such as nitrogen and phosphorus, as well as micronutrients, such as molybdenum. The solid and liquid wastes that remain after digestion are often usable as soil conditioners or fertilizers. The process also greatly reduces the odour problems associated with other methods of organic waste management.

In case biogas is used for electricity, capacities would vary depending on resource and site. Single farm engine capacities are around 100 kW, while centralized pilot systems have reached about 1 MW capacity. Biogas used for electricity production is usually burned in an internal combustion engine and the efficiency of conversion to electricity depends on the size of the machine. Units rated at less than 200 kWe normally operate at an efficiency of no more than 25 per cent, while larger machines—up to 17 MWe—may return a conversion efficiency of up to 36 per cent. The overall system energy efficiency can be boosted to 65-85 per cent by recovering heat from the exhaust and cooling system.

In Europe, the electricity generating capacity based on anaerobic digestion was 300 MW in 1997. According to the European Union Directorate General for Energy, this could reach 1,000-2,000 MW by 2010, and the global capacity could be 10 times the European level. In developing countries where agriculture still forms a central part of the economy, the opportunities for its application appear promising, too, as a waste disposal strategy. In the developed world, anaerobic digestion is likely to be used to dispose of the organic part of domestic waste as environmental regulations become more stringent (3). Anaerobic digestion is primarily used for wastes and manures but it may also be used on starchy energy crops.

The use of gas turbines is likely to become more widespread, certainly at capacities above 800 kWe, when their electrical efficiency equals or betters that of conventional gas engines. Their overall system efficiency can exceed 70 per cent, and the waste heat can be recovered in the form of steam rather than the less valuable hot water produced from internal combustion-based systems. In the longer term, fuel cells and Stirling cycle engines may be used to produce power from biogas. Table 11 gives a summary for biomass electricity generation technologies.

(b) *The cost*

The cost of delivering fuel gas, electricity, or shaft power with a biogas system varies with the characteristics and requirements of a specific application. However, capital investment is an important cost factor in all cases, especially where the capacity utilization rate is relatively low, as it often is in village applications. Operator costs are also important. When electricity is produced using a dual-fuel (producer gas + diesel) engine, the cost of the diesel fuel is also an important cost component.

Large-scale industrial digesters (retained-biomass designs) have much lower costs per unit of gas production (although they typically require greater capital investment) than small unmixed-tank digesters because throughput rates are much higher. A recent estimate for the total cost of methane from a digester (300,000 GJ/year capacity or larger) with a typical industrial feedstock is less than $2/GJ (less than US$ 0.07 per litre of diesel equivalent) under European conditions and about US$ 1/GJ under Brazilian conditions—making this technology highly competitive with many fossil-fuel alternatives.

(c) *The environmental impacts*

Biogas is often, and appropriately so, touted for its positive environmental attributes, which include pathogen destruction and production of a natural, nutrient-rich fertilizer. If pathogen destruction is an objective (as it has been in China), sufficiently long residence times (both Short Residence Time [SRT] and High Residence Time [HRT]) are required in the digester. (With longer residence times, gas yields per unit volume of digester are necessarily lower than when shorter residence times can be used.)

Some precautions are needed in using biogas, particularly for household cooking. Biogas is not toxic, but an accumulation of gas in a closed living space presents explosion and asphyxiation risks. In practice, safety has not been a problem in the vast majority of cases where biogas has been used.

TABLE 11. TECHNOLOGY SUMMARY: BIOGAS FROM ANAEROBIC FERMENTATION

Sale of application	Household or village	Industry or municipality
Energy services	Electricity or shaft power	Electricity
Range of output	3-10 kWe	500-15,000 kWe
Scale of services provided	Village	Industrial facility or electric utility grid
Technical parameters		
Basic equipment	Digester, diesel engine, sludge filler/drier	Digester, gas cleanup, gas engine, sludge filler/drier
Typical biomass inputs	Fresh animal or human manure, crop straws leaves, grasses	Sewage sludge, food-processing or food wastes, distillery effluents, animal manure
Typical gas production		4-8 Nm^3
Inputs per unit output[a/]	~ 14 kg fresh dung[b/] ÷ 0.06 litres diesel fuel per kWh	Varies with feedstock
Useful byproducts	Nitrogen fertilizer pathogen destruction	Reduction of COD, BOD* fertilizer/irrigation
Key to performance	C:N ~20:1 water: solids ~85:1 internal temperature ~35°C	Temperature ~55°C
Technology availability	Designs widely variable, can be built with mostly local materials	Sold/made by companies in many countries
Difficulty of maintenance	Diesel engine maintenance	Moderate
Failure modes	Inadequate feed supply; social or organization problems (e.g. dung collection); lack of skilled labour for repairing structural damage (especially cracking of fixed-dome units)	-
Key cost factors	Capital, diesel fuel, operating labour	Capital

* COD = Chemical Oxygen Demand; BOD = Biological Oxygen Demand.

a/ Typical for Indian cattle dung digesters.

b/ Fresh dung contains ~15 per cent dry solids.

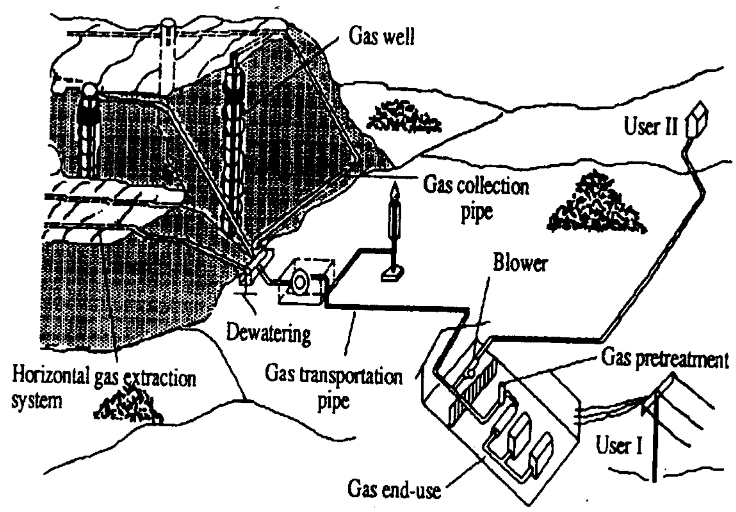
4. *Landfill gas technology*

(a) *The technology*

In many countries, domestic refuse (MSW) is buried in large holes in the ground, generally known as landfill sites. Where these contain a significant amount of organic material and where conditions are right, landfill will produce large amounts of gases called landfill gas (LFG) containing 40-60 per cent methane. This can be collected and burnt to generate power (see figure XXI).

The exploitation of methane generated in refuse landfill disposal sites comprises two stages: collection of the gas and its combustion. Collection is a low-technology procedure that involves drilling into the landfill and installing collection pipes. These are often plastic drainpipes perforated with holes through which the gas enters. A low suction pressure is usually applied to draw in the gas from the surrounding matter. Once a landfill site has been filled, it may be capped with an impermeable membrane to prevent gas escaping except through the collection system. It is normally possible to collect around 30-40 per cent of the gas produced. The calorific value of the gas is much lower than NG.

Figure XXI. Components of a biogas landfill system



The comparison of the gas produced depends on the materials present in the waste and the age of the site and normally contains 40-60 per cent methane; it is treated to remove particulate material and excess moisture before being burned. Some additional cleaning to remove potentially corrosive chemicals may also take place. The purified gas is then used as fuel in an engine. Most LFG to electricity plants operate on gas consisting of about 50 per cent methane. A site can still be used for electricity generation provided that the methane content does not fall below 25 per cent.

(b) *The cost*

Costs of landfill gas and the possibly generated electricity are highly dependent on the site and MSW characteristics. Payback period for systems built in different countries varied between 4.5 and 18 years.

(c) *The environmental impact*

LFG production has several positive environmental impacts that are similar to those of MSW anaerobic digestion processes.

To this end, it has to be noted that although most of the described technologies for biomass electricity are well or reasonably developed, the practical applications of the technology will be dependent on several site-specific issues, as well as the locally available alternatives and the structure of electricity supply in the country.

VI. BIOMASS ELECTRICITY, POTENTIALS AND PROSPECTS IN THE ESCWA REGION

Biomass conversion to useful energy forms has been the subject of several R&D activities and demonstrations in the ESCWA member countries during the last 20 years. However, very little has been achieved for its development to filed applications, especially for electricity generation. In spite of such efforts, biomass resources have not been appropriately assessed or classified in a way that facilitates the evaluation of its potential in the region.

This chapter describes the status of biomass resources assessment and its development status in the ESCWA region, as well as possible criteria for potential evaluation and required further actions.

A. BIOMASS RESOURCE STATUS AND POTENTIAL

1. *Resource assessment*

Several biomass resource assessment studies for both rural and urban areas have been carried out in the ESCWA region, mainly in Egypt, Jordan, the Syrian Arab Republic, the areas under the control of the Palestinian Authority and Yemen. However, the coverage and depth of the studies are either limited or not sufficient to evaluate biomass potential applications.

(a) *Egypt*

Biomass resources assessment have been conducted mainly by the National Research Center (NRC) and the Agricultural Research Center (ARC), and a valuable database has been set up incorporating the information provided in these studies.

Over 20 million tons of agricultural wastes are produced annually in Egypt, derived mainly from agricultural residues and agro-industries. Bagasse (sugarcane residues) and rice husks both provide important sources of energy for their respective processing industries. About 70 per cent of the estimated annual production of 3 million tons of bagasse is used as fuel at the sugar production sites; and of the 40,000 tons of rice husks produced annually, about 15,000 tons are used in the rice mills as fuel.

The per capita generation of municipal solid wastes in cities and towns ranges from 0.2 kilograms (kg) for those with a low standard of living to 0.8 kg for those with higher living standards. At present, total municipal solid waste generation in Egypt is estimated at 30,000 tons per day; around two thirds is produced in the cities, and the remainder comes from suburban and rural areas. Generally, the specific gravity of these wastes (in Egypt) is about 0.3, the moisture content is about 40 per cent, and the calorific value is around 1,600 calories per gram.

(b) *Jordan*

Biomass resource data are scarce, and only a few preliminary studies have been prepared. According to these studies, Jordan produces about 1,500 tons of municipal solid wastes per day, and it is estimated that animal waste resources can be used to produce about 90 million cubic metres of biogas annually. Appropriate quantitative and evaluative assessments of biomass resources need to be conducted.

(c) *The Syrian Arab Republic*

Several studies have been carried out with ESCWA support, and extensive data have been collected on biomass resources. Estimates of the main biomass resources show that there are about 537,000 tons of animal dung; 288,000 tons of chicken droppings; 230,000 tons of human waste; and 34,000 tons of kitchen residues available every year. The studies indicate that 286 million m^3 of biogas could be produced annually in the Syrian countryside.

2. *Criteria for evaluating biomass electricity potential*

The potential for biomass electricity generation in a specific country or a region depends on several issues that are, in many cases, country-specific as well as technology dependent. These issues include:

(a) *The available biomass resources*

The type and quantity of the biomass resources available will determine the possibility and effectiveness of any selected technology. In addition, the location of the available biomass and the relevant transport and costs affect its feasibility. An added resource characteristic is the sustainability of the resources available.

(b) *National energy policy*

The energy sector strategies and policies geared towards the need to develop biomass electricity is naturally an essential parameter in evaluating its potentials. In addition, the measures adopted for such development is also essential

(c) *The prevailing environmental measures*

The environmental measures and applications in the country would highly affect the policies for developing biomass applicants. Such environmental measures include trends for reducing greenhouse gases (GHGs) and the need to solve organic waste treatment and disposal problems.

(d) *Availability of mature technologies*

The maturation level of the available technologies and its possible cost under local conditions can affect the feasibility of applying such technology for biomass utilization, specifically its economics.

(e) *The available local capacities*

The available local institutional, manufacturing, technical, as well as relevant extension services capacities determine the possible local contribution in the developing processes of biomass electricity and consequently the cost of electricity production.

(f) *The finance availability*

Available financial schemes and the comparative level and terms of the finance-required world highly affect the feasibility.

B. CURRENT DEVELOPMENT STATUS

Several ESCWA member countries have directed efforts towards evaluating biomass technologies through R&D studies, demonstration and field-testing. However, the level of activity and the field applications are currently very limited. The following summarizes the current development status.

1. *Biomass R &D and planning*

R&D activities have been carried out to assess biomass resources, evaluate technologies, and explore the potential for their utilization. Examples of the activities undertaken by some member countries in the ESCWA region are presented below.

(a) *Egypt*

Several research and feasibility studies on biomass resources have been conducted in Egypt since the late 1970s. These studies have been led by the NRC, the ARC and the NREA and have dealt with rural, urban and industrial waste resources, as well as the development of the different technologies used. The main technologies that have been considered include anaerobic digestion for the production of biogas, sanitary land filling with gas recovery, incineration, and solid-waste gasification systems.

Many comprehensive studies have been carried out on municipal solid wastes in small towns and in large cities such as Cairo. Technical studies and feasibility assessments have also been undertaken.

A study was conducted in 1996 to evaluate the prospects of energy generation from solid wastes under the Egyptian conditions. Several options were considered, and preliminary assessments have been carried out for four prospective systems with large capacities (about 500 to 1,000 tons of municipal solid wastes per day) for electricity generation; the systems considered would be used for incineration, sanitary land filling (with gas recovery), landfill composting and anaerobic digestion.

In 1982, a detailed study evaluating biomass as an energy source and incorporating a recommended action plan was prepared within the context of Egypt's efforts to develop a renewable energy strategy. In 1991, under the auspices of the Egyptian Environmental Affairs Agency (EEAA) and within the framework of the Environmental Action Plan, a national strategy for the utilization of municipal solid wastes as an energy source in Egypt was prepared.

In addition, the NREA Egypt has developed and built an advanced biomass laboratory, including a set of full-scale equipment and systems for demonstrating and testing of both biological (biogas) and thermal (gasification and briquetting) systems.

(b) *Jordan*

Biomass R&D and demonstration activities have been limited to the following: (i) an experimental biogas digester was constructed in 1993 by the University of Jordan in cooperation with the former Jordanian Electric Authority (JEA) (a limited number of private farms have built similar units); and (ii) a preliminary study was carried out by the Ministry of Mineral Resources and the Amman Municipality to determine the feasibility of using municipal solid wastes for electricity production. A pilot project will be financed by the GEF for the treatment of 50 tons per day of municipal solid wastes, which are expected to produce 7,800 m^3 of biogas that can be used to generate 1 MW of electricity.

(c) *The areas under the control of the Palestinian Authority*

A study assessing the prospects for the use of different biogas technologies for electricity generation is being conducted in cooperation with European firms as part of a European Union-financed project known as INTERSUDMED.

(d) *Yemen*

Within the framework of ESCWA technical support to Yemen, a study entitled "Biogas technology and the development of rural women in Yemen" (E/ESCWA/SD/1993/1) was conducted in 1987. The main objective of the study was to assess the prospects for the use of biogas technologies in Yemen; it was concluded that these technologies could greatly benefit the rural areas of the country. The study recommended the development of a long-term strategy for enhancing the use of biogas technologies in Yemen.

2. *Biomass energy demonstrations and field-testing*

Biomass technologies have been demonstrated and field-tested in Egypt, Lebanon, the Syrian Arab Republic and Yemen.

(a) *Egypt*

Since the late 1970s, different Egyptian institutions, in particular the NRC and the ARC, have been involved in the design, construction, testing and operation of different prototype digesters.

The NRC has demonstrated biogas technologies in three villages: Manawat village in Giza; Omar Makram village in the El-Tahrir province; and Shubra Kas village in Garibiyah. Digesters with a capacity of between 6 and 50 cubic metres were designed for the Misr Aluminium Company. At least 10 digesters with different designs have been installed and evaluated, and some have been operating since 1980. Family-sized and large-scale mechanized units have been tested as a source of energy and for waste recycling and management. The gas produced has been used for cooking, heating, refrigeration and the production of electrical power. The ARC, through a (Food and Agriculture Organization of the United Nations) FAO-financed project, has demonstrated about 200 units of different sizes using agricultural residues: animal dung and poultry farm manure. Improved designs have been developed locally by both organizations.

The Energy and Electricity Research Council (EERC) of the Academy of Scientific Research and Technology (ASRT) has sponsored a project to develop modular designs for biogas digesters. A number of designs have been developed, some of them for solar-assisted units.

In the late 1980s, a number of demonstration plants for municipal solid waste treatment were set up and linked to a well-designed sanitary landfill with a daily capacity of 11,000 tons.

Five imported composting plants were set up during the period 1983-1986 in the large cities. Recently, the first local plant was erected in Zagazig and a second is planned for Alexandria.

The first locally designed and manufactured hospital-waste incinerator with a capacity of 100 kg per hour was recently produced, and the possibility of establishing a larger central incineration facility has been explored. These efforts have been led by the Consulting Fund of the Ministry of Higher Education and the State for Scientific Research in collaboration with the EEAA and local industries.

(b) *Jordan*

A techno-economic feasibility study for 1-MW size electric power generation from municipal solid waste has been carried out in cooperation with UNDP. The project was commissioned in March 2000. The project, which is located at the Amman municipal waste disposal site, has cost JD 4 million and provides energy savings equivalent to 17,000 TOE/y.

Direct combustion of biomass provides some energy for cooking and heating in some rural areas. The utilization of bio-energy in the form of biogas from animal and domestic wastes has also been investigated with the aim of introducing a family fermentation unit that produces biogas for domestic purposes.

It has been estimated that animal and solid wastes in Jordan represent an energy potential of about 100,000 TOE annually.

(c) *Lebanon*

Mercy Corps, a non-governmental organization (NGO), has designed and built three biogas digesters for rural areas within the framework of a community development project financed by USAID.

(d) *The Syrian Arab Republic*

A prototype family biogas digester was designed and built at the Mechanical and Electrical Engineering College. Another two digesters have been built and set up in rural areas. Both digesters are operating, and the data collected from them will be analysed and used for the development and diffusion of biogas technologies. Three integrated biogas systems in Dair Al-Fardews village (Homs) have been constructed within the local community development project.

(e) *Yemen*

Biogas field demonstration projects have been executed by ESCWA and funded by AGFUND, UNIFEM and the Netherlands Government Trust Fund. These projects have included three biogas demonstration plants with different designs, which were constructed in a Yemeni village. These biogas units had been designed to suit local conditions in the rural areas of southern Yemen. The initial success of this activity led to the construction of 22 family-size integrated biogas systems serving 32 families in Mansourat Al-Habeel village in Yemen.

3. *The commercial status of biomass technologies*

In spite of the achievements described above and the fact that biomass energy can contribute significantly to sustainable development, particularly in rural areas, the market penetration of biomass technologies specifically for electricity production has been very limited owing to various economic, technical and social constraints that have hindered their replication/adaptation. Efforts are being made to promote biomass energy applications, and the only exception is the huge biogas plant of 22,000 m3-volume digester used for electricity production (18 MW) in El-Gabal El-Asfer sewage treatment plant for Cairo, Egypt.

4. *Technology transfer and local manufacturing*

In Egypt, local designs for biogas digesters have been developed based on Chinese and Indian designs. The locally designed and constructed composting plant and pilot units have proved to be cheaper and more cost-effective than the imported facilities and equipment. However, no regular local production has yet been achieved. A similar situation exists in the Syrian Arab Republic and Yemen.

5. *Standards, codes and certification*

No standards or codes have been issued in the region for any of the biomass energy technologies, components or systems. However, performance evaluation and other types of tests are being conducted at the NRC, the ARC and the Egyptian Renewable Energy Development Organization (EREDO) biomass laboratories in Egypt, which include testing facilities for both biological and thermal biomass systems.

C. FUTURE PROSPECTS

Although the availability of different types of biomass in the ESCWA member countries is proven, appropriate assessment and classification data are not available. This fact represents quite a constraint for possible evaluation of the application potential and future prospects of technologies that are currently mature. Efforts should be directed by national authorities, ESCWA and other regional organizations to upgrade the available database so as to facilitate the required actions in this regard.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. *Wind energy electricity generation*

The study outcome of this report leads to the following conclusions:

(a) *Wind resources and technologies*

(i) *The wind resources potentials*

The economics of wind power depend strongly on wind speed. Long- and short-term wind speed measurements will normally be needed to ascertain the wind regime. Only when these figures are available can the economics of the project be determined with any accuracy.

In general, studies proved that the global potential of wind energy is large, with the technical potential of generating electricity onshore estimated at 20,000-50,000 terawatt-hours per year and when investigating the potential, special attention should be paid to possibilities offshore.

(ii) *Wind technologies development*

As a result of intensive basic and applied researches over the last 20 years, development and demonstration efforts are exceptional in several industrialized countries, with leading research centres and industries in Denmark, the Netherlands, the United States of America, Germany and others. The technologies of wind turbines for electricity generation are now in full progress.

Meanwhile, wind power has enjoyed fast-paced development in recent years, mostly in the industrialized world, with Germany, the United States, Spain and Denmark emerging as the fastest-growing wind markets worldwide in 1999. The main development features include:

1. Turbine sizes increased steadily and, by 1998, most new wind employed turbines have capacities of between 600 kW and 750 kW.

2. The development of the wind farm concept, which resulted in the promotion of the use of wind electricity generation to large-scale grid-connected applications. However, the permissible wind penetration rate is usually between 10-15 per cent of the grid capacity.

3. The total installed capacity in January 2001 reached 16,461 MW, including 65 MW in Egypt compared with 4,779 MW in 1995. In addition, the projected wind power estimated 20,000 MW for 2002 with a 10 per cent growth up to 2016 to reach saturation in between 2030-2035 at about 1.9 terawatts/year. Under these assumptions the cost can come down to US$ 0.027/kWh on average.

4. The main technology development features expected in the coming decade, based on the achieved development trends since the 1970s, are wind turbines becoming larger, wind turbines becoming more controllable and grid-compatible, wind turbines will have fewer components, and time to market will become shorter than project preparation time.

5. The study survey shows that system future aspects would include:

(a) Wind turbines becoming larger, with the average size installed in 1998 at 600 kilowatts, up from about 30 kW in the mid-1970s. Turbines of megawatt size are being developed and should soon be commercially available;

(b) Costs have to come down further, requiring development of advanced flexible concepts and dedicated offshore wind energy systems. Cost reductions up to 45 per cent are feasible within 15 years. Ultimately, wind electricity costs might come down to about US$ 0.03 per kilowatt hour;

(c) The environmental impact of wind turbines are limited, with noise and visibility causing the most problems, which in turn increases public resistance to the installation of new turbines in densely populated countries.

(b) *Potentials of wind electricity in the ESCWA region*

(i) *Wind resources status*

Wind resource measurements are regularly taken by most of the meteorological organizations in the ESCWA member countries. However, they are not as precise as to satisfy the requirements for wind statistics for energy assessment and electricity potentials in the ESCWA member countries. Based on the currently available wind data, the wind resources in the ESCWA member countries can be classified into three groups:

a. ESCWA member countries with limited or no potential for wind electricity generation: Lebanon, Palestine, Saudi Arabia and the United Arab Emirates;

b. ESCWA member countries with moderate potential for wind electricity generation: Bahrain, Kuwait, Oman, Qatar and Yemen;

c. ESCWA member countries with promising potential for wind electricity generation: Egypt, Jordan and the Syrian Arab Republic (Golan Heights).

It should be noted that appropriate and accurate assessments may identify a specific site that could be classified differently than shown above.

(ii) *Criteria for evaluating wind electricity potentials*

The potential for wind energy utilization for electricity generation depends on several factors but with a basic need for good wind resource sites. The following set criteria for evaluation of such potential in a specific ESCWA member country includes: (1) the available wind resources, (2) energy strategies and policies, (3) the possible wind penetration, (4) prospective site conditions, (5) available local capabilities, and (6) financial availability.

(iii) *Prospects for wind electricity development in the region*

With the exceptions of Egypt, Jordan and the Syrian Golan Heights, the preliminary resources data do not show promising potentials for wind electricity generation in most of the ESCWA member countries.

In Egypt, theoretical potentials for wind electricity in the Gulf of Suez were estimated to be 20,000 MW, while the official development programme total by the year 2010, as indicated in chapter VI of this report, is only 600 MW.

2. *Biomass electricity generation*

(a) *Biomass resources and technologies*

Biomass resources can be classified into two main groups: *primary biomass resources*, which are crops specifically planted for energy production through combustion, gasification or fermentation processes, and *secondary biomass resources*, which are produced as a by-product of plantation residues, animal waste, sewage and municipal solid waste (MSW).

If biomass is to make a major contribution to electricity generation, then crops will need to be grown specifically for energy production, and greater emphasis should be directed to effective waste collection and disposal techniques that could easily involve waste combustion.

There is a variety of modernized biomass technologies that can efficiently convert biomass resources into clean, convenient gaseous and liquid energy carriers to be used for electricity production. A range of technologies for producing fuels from biomass exists and can be used for electricity generation. These are: (1) direct combustion (conventional and improved [fluidized bed]); (2) gasification; (3) anaerobic digestion; and (4) landfill gas production. Chapter V gives a briefing on the concept and development status of each of these technologies.

The choice of technology can drastically affect the economics of biomass electricity and limit the size of the plant producing it. In general, there is a considerable potential for the development of biomass electricity production, particularly in the context of CHP. With the exception of fuel cells, most of these technologies are mature, and there are many examples already in the marketplace. For some, their viability is owing to subsidies and other financial incentives in the face of cheap fossil fuels.

Capital costs for biomass burning power plants based on conventional steam technology tend to be higher than for coal- and gas-fired plants. Taken together with the relatively high cost of the fuel, this makes biomass uneconomical as a base-load power generation technology. However, there are circumstances, for example at a sugar processing factory or a wood yard, where the waste is free and already at the site and the economics are much more favourable.

When biomass is burnt in a power station, it produces CO_2 in exactly the same way as coal or natural gas combustion produces CO_2, however, as it grows, bioplantaton captures carbon dioxide from the atmosphere and uses it to produce new plant material. In other words, biomass cycles carbon between the fuel and the atmosphere, and the net effect on the atmospheric concentration of CO_2 of burning biomass is effectively zero. The burning of agricultural wastes has an additional benefit of removing a waste disposal problem when the ash can often be distributed on land as a fertilizer.

(b) *Biomass electricity, potentials and prospects in the ESCWA region*

Several biomass resource assessment studies for both rural and urban areas have been carried out in the ESCWA region, mainly in Egypt, Jordan, the Syrian Arab Republic, the areas under the control of the Palestinian Authority and Yemen. However, the coverage and depth of the studies are either limited or not sufficient to evaluate biomass potential applications.

The criteria for evaluating biomass electricity generation potential in a specific country or a region depends on several issues that are, in many cases, country-specific, as well as technology-dependent. These issues include: (a) the available biomass resources; (b) national energy policy; (c) the prevailing environmental measures; (d) availability of mature technologies; and (e) the available local capacities.

Several ESCWA member countries have directed efforts towards evaluating biomass technologies through R&D studies, demonstration and field-testing with exceptional examples of field applications, particularly for electricity generation. However, the achievement and level of activity for electricity generation, particularly for field applications, are currently very limited, as shown below:

(i) *R&D and demonstration*

Several research and feasibility studies were carried out in order to investigate the potential applications of biomass in the ESCWA member countries. However, it was determined that only a few were suitable for electricity generation. Biomass technologies have been demonstrated and field-tested in several ESCWA member countries; *in Egypt*, family-sized and large-scale mechanized biogas units have been tested as a source of energy, including electrical power and for waste recycling and management; *in Jordan*, a 1-MW size electric power generation unit from municipal solid waste was commissioned in March 2000. The project is located at the Amman municipal waste disposal site, saving the equivalent of 17,000 tons of oil per year; and *in Yemen*, biogas systems were demonstrated with ESCWA support in a Yemeni village. The initial success of this activity led to the construction of 22 family-size integrated biogas systems serving 32 families in Mansourat Al-Habeel village in Yemen.

(ii) *Market penetration*

The market penetration of biomass technologies, specifically for electricity production, has been very limited owing to various economic, technical and social constraints that have hindered their replication/adaptation. The only exception is the huge biogas plant with a 22,000 m^3-digester volume used for electricity production (18 MW) at El-Gabal El-Asfer sewage treatment plant for Cairo, Egypt. However, no regular local production has yet been achieved. No standards or codes have been issued in the region for any of the biomass energy technologies, components or systems.

(iii) *Future prospects*

Although the availability of different types of biomass in the ESCWA member countries has been proven, appropriate assessment and classification data are not available. This fact represents quite a constraint for possible evaluation of the application potential and future prospects of technologies that are currently mature. Efforts should be directed by national authorities, ESCWA and other regional organizations to upgrade the available database so as to facilitate the required actions in this regard.

B. RECOMMENDATIONS

In view of the study outcome, it is clear that although both wind and biomass electricity generation can have promising potentials in some ESCWA member countries, its development and utilization still are facing difficulties—particularly the absence of appropriate resource assessment—to enable potential evaluations to be made with reasonable accuracy and to facilitate project designs and technology selection. Moreover, the limited consideration given to the development of two such valuable sources within the national energy plans is an added constraint to its development.

In view of the above and in line with the general conclusions and recommendations of the study, the following core actions are recommended:

1. Countries in the region, in cooperation with ESCWA and other active regional organizations, should direct concerned efforts towards upgrading the resource databases on wind and biomass through accurate and advanced measurement and analysis techniques. The product of such assessments should be able to serve the objectives of potential assessment and project designs.

2. Wind and biomass development—as essential components of renewable energy resources—should be incorporated as an integral part of the national and sectoral energy planning.

3. The planning processes for the development of renewable energy applications, including wind and biomass, should take into account the whole integrated spectrum of expertise and capabilities needed and consideration should be given to the upgrading of the national contributions to it, particularly maximizing the locally produced components, the contribution of national expertise and the operation and maintenance capabilities.

ENDNOTES

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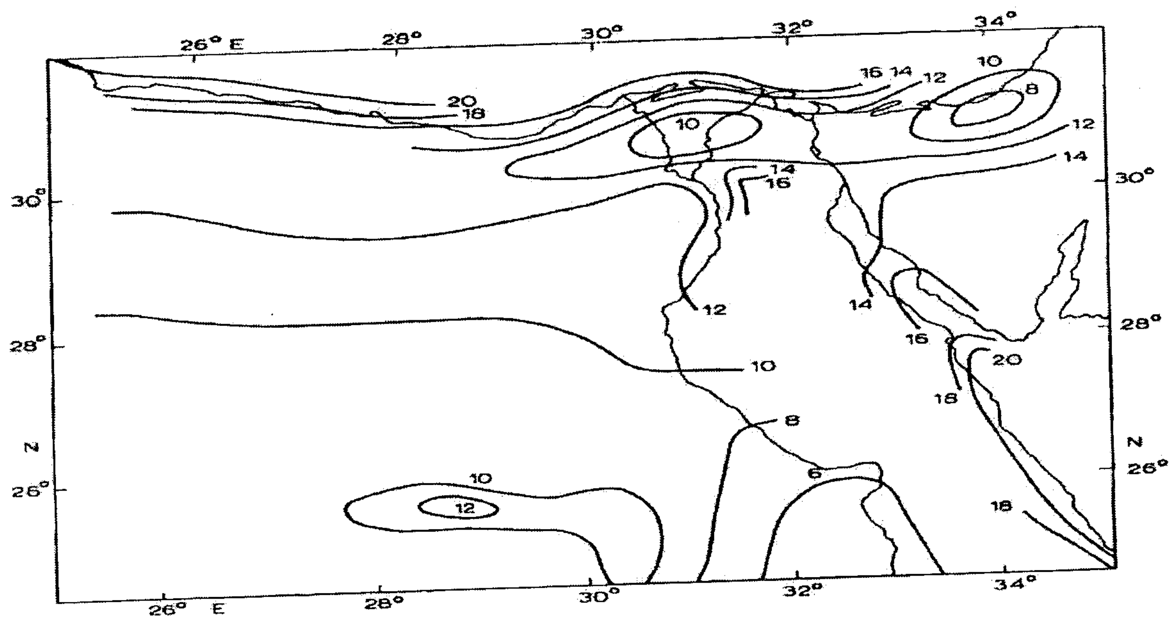
Annex

ASSESSMENT OF WIND ENERGY RESOURCES (CASE OF EGYPT)

1. *Preliminary investigations*
(*Based on the data obtained from the national meteorological stations*)

The overall climate of Egypt is described in various textbooks and climatologies, of which the work by Griffiths and Soliman (1972) go into some detail. Their description encompasses the pressure distribution and general circulation, radiation, sunshine, temperature, precipitation, snow, thunderstorms, hail, evaporation, relative humidity and surface wind—with reference also to earlier work by others. Their descriptions are presumably built upon the measurements made at standard meteorological stations in the synoptic network. The surface wind conditions are summarized (Griffiths and Soliman 1972) in a map of Egypt (see figure 1).

Figure I. Annual mean wind speeds over Egypt in km/hour according to Griffiths and Soliman (1972); 1 km/hour corresponds to 0.28 m/s



The map indicates that the highest wind speeds are found in the western part of the Mediterranean coast, along the Gulf of Suez, and in the northern part of the Red Sea. While this is roughly in accordance with more recent studies, the wind speed values shown on the map for the Gulf of Suez are apparently far too low, and the geographical variation within the Gulf can only be partly confirmed. No information is given on the exact measuring procedure or height above the ground, so the reason for this is not known.

The need for a more precise quantification of the wind climate of Egypt was recognized early and a number of wind resource assessment studies were initiated in the 1970s and 1980s. These activities were summarized by Renne, Elliott and El-Bassyouni (1986), who also published a map showing the distribution of seven wind power classes over Egypt (see figure 2).

They reanalysed existing wind data obtained at stations run by the Egyptian Meteorological Authority and then verified and detailed these resource estimates through additional wind measurements at key locations. For this purpose, a number of wind monitoring stations were erected along the Mediterranean and Red Sea coastlines. The analysis further used climatological data on winds aloft and maps of pressure patterns and airflow, as well as topographical maps, in estimating the wind resources of the data-sparse areas. The resource estimates were calculated from measured distributions of mean wind speed or, in cases where only average wind speeds were available, by assuming that the wind speeds are distributed according to the Rayleigh distribution.[1] The wind power estimates depicted in figure 2 apply to "areas free of local obstructions to the wind and to terrain features that are well exposed to the wind, such as open plains, plateaus, and hilltops. Within mountainous areas, the wind resource estimates apply to exposed ridge crests and mountain summits" (Renne et al. 1986). The topography of the terrain is thus taken into account in the construction of figure 2, albeit in a qualitative way.

Figure II. Annual average wind power estimates for Egypt according to Elliott et al. (1986)

The distribution of six so-called wind power classes are shown on the map, class I being all white and class 6 all black:

Power class	Wind speed m/s	Energy density W/m^2	Power class	Wind speed m/s	Energy density W/m^2
1	<4.4	<100	4	5.6-6.0	200-250
2	4.4-5.1	100-150	5	6.0-6.4	250-300
3	5.1-5.6	150-200	6	6.4-7.0	300-400

The wind speeds and energy densities correspond to a height of 10 metres. A seventh class with V>7.0 m/s and E>400 Wm^2 is also defined, but cannot be identified on this map.

The wind climate of the Gulf of Suez range from class 3 (5.1-5.6 m/s) in the northernmost part of the Gulf to class 6 (6.4-7.0 m/s), which covers the southernmost three fourths of the Gulf. At one station, Ras

[1] The Rayleihg distribution is identical to a Weibull distribution with k=2.

Ghareb, the data even indicate class 7 (7.0-9.4 m/s), but this is attributed to the location of the station on a well-exposed ridge (Renne et al. 1986) and may not be representative of the terrain of the region in general.

For the Sinai Peninsula, wind data has also been collected and summarized by Manes et al. (1980). However, even though these data have been referenced in the international literature (e.g. Nof and Paldor 1994), the report is apparently not publicly available. Average annual wind speeds for stations along the east shore of the Gulf of Suez reported by Nof and Paldor (1994) are: 6.0 m/s close to the city of Suez; 8.9 m/s at Ras Sedr (200 m a.s.l.); and 7.6-7.7 m/s close to El-Tor in the southern part of the Gulf. These average wind speeds are based on 2-7 years of data and are consistent with the picture shown in figure 2.

2. *Recent study*
(Based on the measurements done for wind energy purposes)

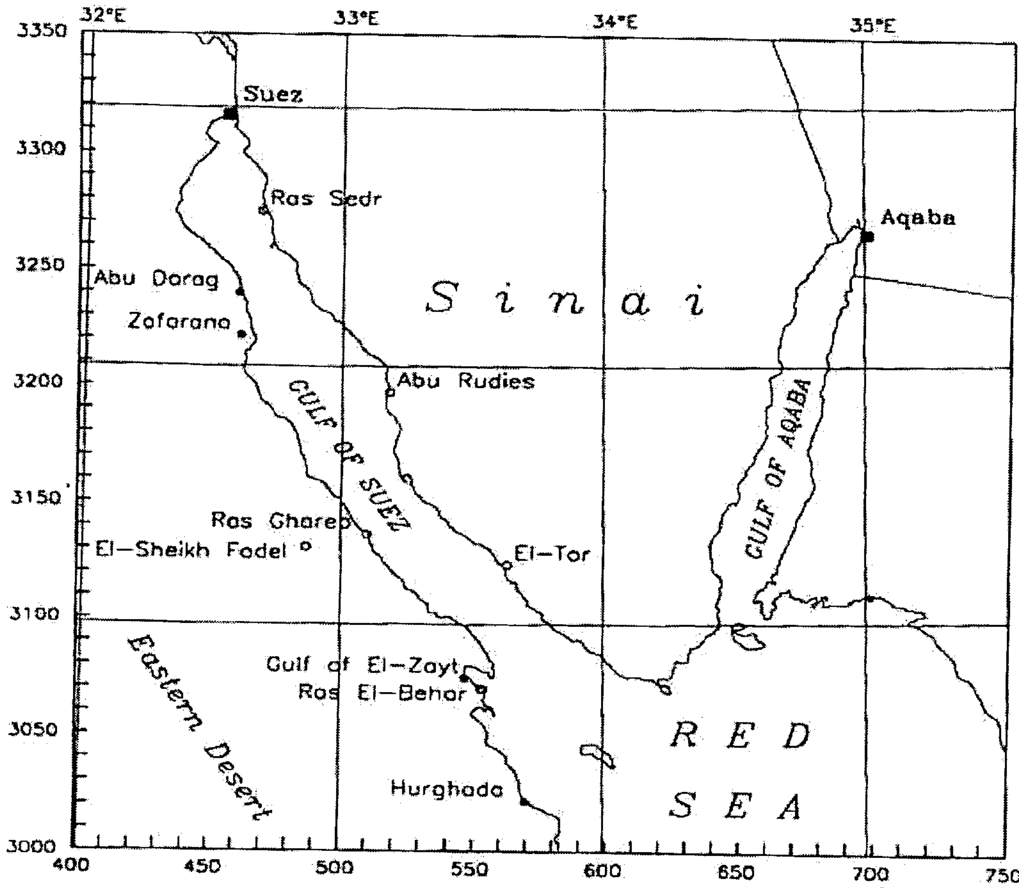
(a) *Wind Atlas for the Gulf of Suez (1991-1995)*

An important characteristic of wind energy is that the power output of a wind turbine is proportional to the third power of the wind speed. Therefore the precision requirements of wind speed statistics for energy assessments are higher than for most other purposes. Another noteworthy characteristic of the wind is the seasonal and year-to-year variations of the wind conditions. An accurate determination of wind climatologies must take into account these variations; therefore several years of wind data must be used in the analysis. In 1990, the available wind data for the Gulf of Suez were reevaluated by the New and Renewable Energy Authority and Riso National Laboratory (Denmark) with the purpose of making the data useful for wind atlas analysis. Following the methodology provided by the European wind atlas (Troen and Petersen 1989), and in order to establish a wind atlas for the Gulf of Suez, the sites where wind data had been collected were described with respect to the distribution of roughness areas and the occurrence of sheltering obstacles. Consequently, regional wind climatologies for these stations were established. The survey concluded that the wind conditions in the Gulf of Suez indeed seemed favourable for wind energy utilization, but recommended that four new stations be erected to improve the estimates of the wind energy potential at the two most promising and probable sites for construction of large wind farms. Masts were therefore erected at Abu Darag, Zafarana, Hurghada and the Gulf of El-Zayt in the spring of 1991. The aim of the Wind Atlas for the Gulf of Suez is to establish the meteorological basis for the assessment of the wind energy resources along the Gulf of Suez and in the northern Red Sea. The main objective has been to provide reliable and accurate wind atlas data sets for evaluating the potential wind power output from large electricity producing wind-turbine installations. In addition, the Wind Atlas provides data and some guidelines for the meteorological aspects of the detailed sitting of large and small wind turbines.

The study employs wind speed and direction measurements taken from 1991 to 1995 at four meteorological stations along a 250-km stretch of the Gulf of Suez and the northern Red Sea. In addition, historical data from five other stations in the Gulf have been analysed. The four 25-m masts were erected specifically for the wind study, but provide information on other climate statistics as well: atmospheric pressure, air temperature, air temperature gradient, atmospheric stability, wind speed profiles, extreme wind speeds, and gustiness of the wind. Satellite imagery obtained from *NOAA 11 AVHRR* data are used to map land and sea surface temperatures.

The wind data from the nine stations are analysed using the Wind Atlas Analysis and Application Program (WAsP), following the procedures and guidelines of the European Wind Atlas. For the four main wind atlas stations, the accuracy of the wind speed measurements has been secured by wind tunnel calibration of the cup anemometers (see figure 3). The roughness of the terrain has been assessed from topographical maps and aerial photographs, as well as during site visits. Furthermore, the aerodynamic roughness lengths of typical desert surfaces have been estimated from wind profile analysis. The height variations of the terrain—used for assessing the influence of the orography on the wind measurements and wind climate estimations—are described in digital terrain models, which have been obtained by digitization of topographical maps. The study finally employs the results of previous investigations, as well as satellite imagery obtained from *NOAA 11 AVHRR* data, in an effort to validate the magnitude and a real distribution of the wind resource.

Figure III. Overview map of the study area



The Gulf of Suez, the northern Red Sea, the Gulf of Aqaba, and the Sinai Peninsula. The four main wind atlas stations (*), as well as several auxiliary stations (o), are shown on both sides of the Gulf of Suez. Cartesian map coordinates are in kilometres, UTM zone 36.

The Wind Atlas for the Gulf of Suez documents the existence of a widespread and high wind energy resource along the Gulf of Suez, even higher than was hitherto assumed. With mean wind speeds and energy densities of 8-12 m/s and 500-1,400 W/m^2, respectively, estimated at a height of 25 m over roughness class 0 (water), the wind resources are comparable to those of the most favourable regions in northwest-Europe. The resources, however, are not evenly distributed over the region and large horizontal gradients in the wind resource must be expected, especially going inland from the coast.

The west shore of the Gulf of Suez—from Abu Darag in the north to Ras El-Behar in the south—is characterized by mean wind speeds and energy densities of 10-10.5 m/s and 830-970 W/m^2, respectively, estimated at a height of 25 m over roughness class 0. The stations analysed in the Wind Atlas therefore indicate that the near-coastal wind energy resource is consistently high along the west shore of the Gulf of Suez. The inland gradient of the wind climate cannot be described in detail from the data available; however, one inland station 20 km from the coastline (El Sheikh Fadel) indicates a gradient on the order of 0.5 m/s per 10 km. In the Zafarana region, this decrease in the wind resource with increasing distance from the coastline is apparently not found, at least over the first 5 km from the coast.

The east shore of the Gulf of Suez—from Ras Sedr in the north to El-Tor in the south—seems to have a somewhat lower wind resource than the west shore; however, the information for this part of the Gulf is based on about one years' worth of data from two stations only. These indicate mean wind speeds and energy densities of 8.3-9.3 m/s and 530-630 W/m^2, respectively, estimated at a height of 25 m over roughness class 0. With only two stations, neither of which are instrumented to the standard of the main wind atlas stations, the resource estimates given in the Wind Atlas for the eastern shore are therefore less detailed and reliable than for the west shore.

For the northernmost part of the Gulf of Suez—north of the Abu Darag lighthouse and Ras Sedr—the wind resources are most likely lower than described above and decreasing towards the north. Even though no wind atlas analysis has been carried out for this part of the Gulf, a fairly low wind resource is indicated by published mean wind speed values for the city of Suez, as well as by previous wind resource investigations. The nature of the atmospheric circulation and topographical features of this region seem not to favour high wind speeds; this is further supported by the common observation that the sea surface is usually calm in this area and white caps are only seen when going further south.

The southernmost part of the Gulf of Suez—where the Gulf of Suez widens out into the Red Sea—seems to be a region of large horizontal gradients in the wind resource. The highest wind resource recorded for any site in the Gulf of Suez is found here, at the station on the west shore of the Gulf of El-Zayt. The characteristic mean wind speeds and energy densities are about 12 m/s and 1,400 W/m^2, respectively. Historic data from a nearby site, however, show an almost 20 per cent lower mean wind speed. This difference could be partly caused by the two different and rather short observation periods, as well as by the fact that the stations are of quite different types, but it also suggests that this part of the Gulf of Suez experiences large gradients in the resource.

A large gradient in the wind energy resource is also apparent between the southernmost part of the Gulf of Suez and the northern part of the Red Sea. At the Wind Energy Technology Center in Hurghada, the characteristic mean wind speeds and energy densities are about 7.7 m/s and 425 W/m^2, respectively. This significant decrease in the wind resource from the values found in the Gulf of Suez takes place over less than 50 km.

The wind atlas methodology originally developed for wind resource assessment and sitting in Europe, which has proven very useful in the extreme climatic conditions of the desert. Applied with care, it can provide accurate predictions of the wind climate at candidate sites for wind turbines along the Gulf of Suez and northern Red Sea, and the experience obtained can be used in other places with a similar climatology and geography.

The reliability of wind power calculations based on the statistics in the Wind Atlas for the Gulf of Suez depends on the reliability of the data from the particular station from which the statistics have been derived, i.e., on the quality of the data and the amount of information available. Secondly, it depends on the complexity of the terrain at the meteorological station as well as at the sites of interest. Finally, the geographical variability of the wind resource will necessarily add to the uncertainty of the estimates. It must be stressed that the spatial variability of the wind resource in the Gulf of Suez is only known in a fairly broad outline.

Example from the Wind Atlas for the Gulf of Suez (1991-1995)

Wind statistics and climatologies

The climatological data for each station used in the study are presented in tables and graphs. For each station, the tables give the calculated regionally representative wind climatology obtained from the station data by applying the Wind Atlas analysis, together with a summary of the raw data and the measuring conditions. The raw data and some derived quantities are furthermore shown graphically in so-called wind climatological fingerprints (Troen and Petersen 1989). The full descriptions given below pertain to the four main wind atlas stations: Abu Darag, Zafarana, Gulf of El-Zayt, and Hurghada WETC.

Each station summary is printed on four pages. The first page contains:

(a) The station description;
(b) The station topography;
(c) The topographical model corrections.

The second page contains:

Several raw data summaries and graphs

The third page contains:

(a) The wind climatological fingerprint;
(b) The seasonal and year-to-year variation of wind speed.

And the fourth contains:

(a) The calculated regional Weibull parameters;
(b) The calculated regional mean wind speeds and energies.

The presentation of the data is explained in detail in the following sections.

1. *The station description*

The station description comprises the geographical location, a description of the setting and surroundings of the station, a station topographical map, and a summary of the corrections used in the analysis.

Name of station: The names of the stations are those used in previous reports, and they are spelled accordingly.

Geographical coordinates: The latitude and longitude of each station are given in degrees, minutes and seconds. The positions were plotted on topographical maps during visits to the sites by taking bearings to a number of characteristic landmarks in the vicinity of the stations. The positions have further been verified using a GPS (Global Positioning System) receiver.

Grid coordinates: The Cartesian grid coordinates consist of the Easting and Northing in full metres. For Abu Darag and Zafarana, the positions are given in the so-called Red Belt kilometre grid (30°N = 810 km, 31°E = 615 km). For the Gulf of El-Zayt and Hurghada WETC, the positions are given in the Green Belt kilometre grid (30°N = 1,100 km, 35°E = 300 km). Geodetic datum: Az Zahra' 1874.

Altitude: The elevation of the station is given in metres above mean sea level (m a.s.l.). Vertical datum: mean sea level Alexandria 1906.

Station description: The overall setting of each station is described, i.e. major terrain features such as distance from the sea, lakes, rivers, forests, mountains, etc. Major obstacles close to the anemometer may also be mentioned, as well as other information regarded as significant for the interpretation of the station statistics.

Station topographical map: The topographical map shows the digitized contour lines used in the orographic flow model, as well as the areas of different roughness length used by the model to calculate the roughness rose. The information was obtained by digitization of the first edition Egyptian Series 1:50 000 maps, which are compiled from aerial photography taken in 1988 and completed and verified in 1989. Additional information on the roughness of the terrain was obtained from 1:80,000 aerial photographs and from field visits to the sites in 1994. Distance between map tic marks is 1 km, contour line intervals are 10 m and 20 m.

Topographical model corrections: The wind speed correction factors (in per cent) and wind direction correction angles—to allow for sheltering obstacles and the effects of roughness change and orographic forcing—applied in the calculation of the Wind Atlas tables are given in a separate table below the station topographical map. If a station has been corrected for sheltering and roughness change only, there are no corrections to the wind directions.

Raw data summaries: The raw data summary comprises the distributions of wind measurements in tabular and graphical form, as well as tables of the daily, seasonal and year-to-year variations of mean wind speed.

Distribution of wind measurements: This table gives the sectorwise distribution of the raw wind speed measurements and the distribution of wind speeds within each sector. The frequency of occurrence of the winds in the sectors is given in per cent, whereas the distribution of wind speeds is given in per mille (tenths of per cent), i.e. normalized to 1,000 within each sector. The table pertains to the anemometer height in metres above ground level (m a.g.l.) and the measurement period listed above the table. Note that the format of the time given is YearMoDaHoMi, e.g. 199112312105 means December 31, 1991, at 21:05. A Weibull distribution function has been fitted to the wind speed distribution in each sector. The resulting Weibull A- [m/s] and k-parameters are listed in the last two columns of the table.

Wind rose and histogram: The wind rose shows the joint distributions of wind speed and direction. Wind direction is shown in twelve 30°-sectors and the distribution of mean wind speeds, U, in each sector is given in four classes:

$0 < U < 3, 3 < U < 6, 6 < U < 9, 9 < U$ m/s.

The histogram shows the total distribution of wind speeds (bar graph) in the processed time-series. A Weibull distribution function has been fitted to the data and is shown with a full line.

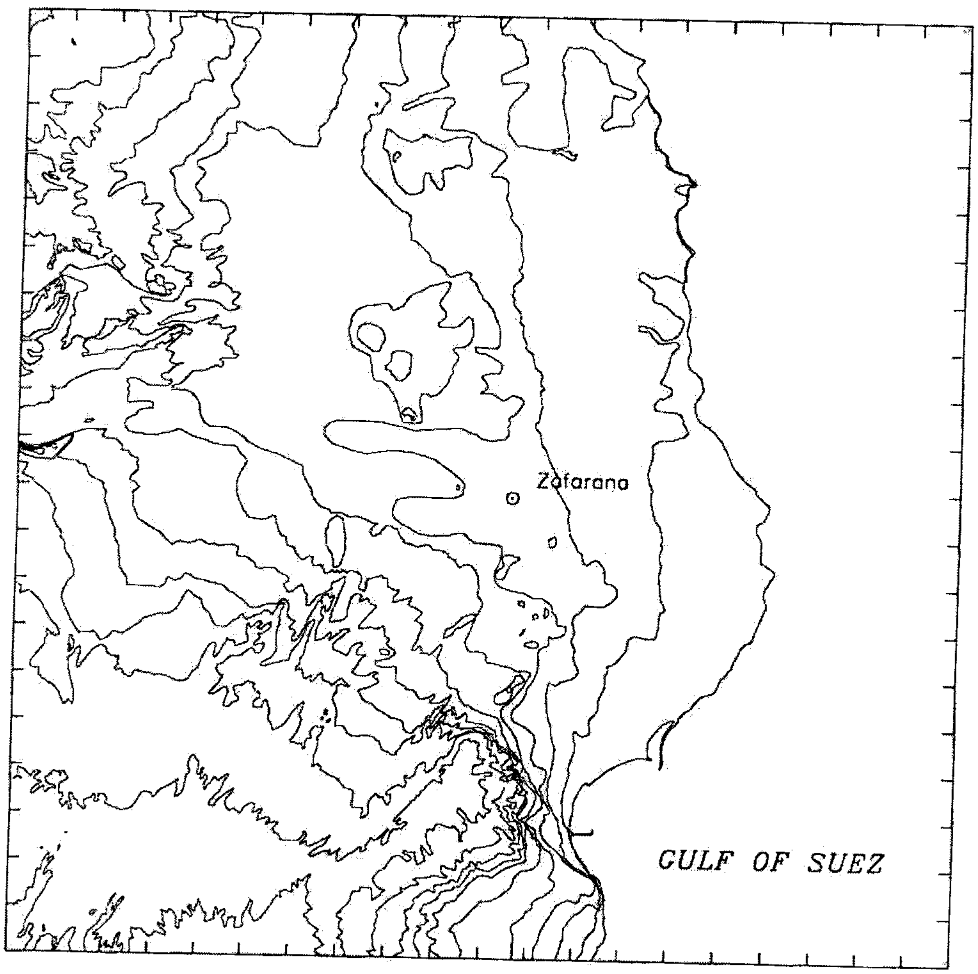
Daily and annual variation of wind speed: This table gives the mean wind speed as a function of time of day and month of year. The time of day is given as Egyptian Standard Time, equivalent to Universal Coordinated Time +2 hours.

Zafarana

29° 06′ 49″ N 32° 36′ 33″ E	E 771 500 m N 712 825 m	25 m

The Zafarana mast is situated about 80 m S of the Zafarana-El Wasta road, approximately 5 km W of Zafarana along this road (map sheet: NH 36 F3a). The distance to the coastline of the Gulf of Suez is 5000 m in an easterly direction. There are no sheltering obstacles close to the mast. The surface consists mostly of sand and gravel with a roughness length of less than 0.01 m. To the NW and S the wide valley is bordered by the North and South Galala Plateaus, respectively, which rise to more than 1000 m.

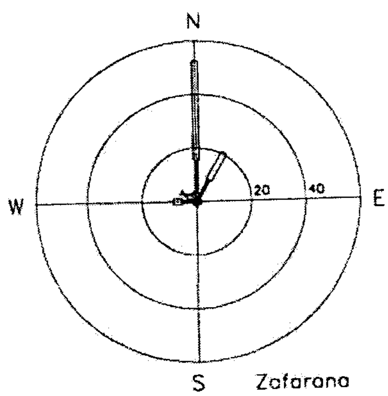
Field notes: The bearing to the radio antenna is 285.5° and to the light house 092°. The distance from the mast to the road is 77 m and the distance from the road crossing in Zafarana to the mast is 5 km. These bearings and distances give a position of the mast of approx. N 712 825 m, E 771 500 m.

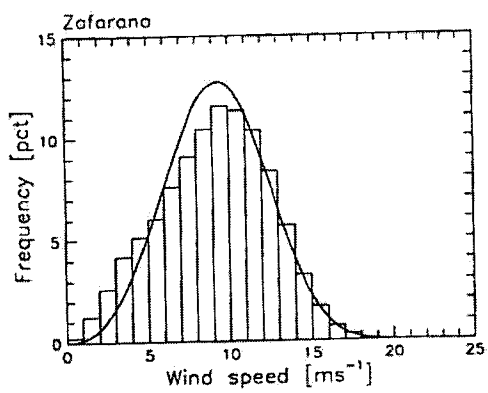


Sector	Input		Obstacles		Roughness		Orography		z_{0m}
0	0.0	0.0	0.0	0.0	−2.3	0.0	−2.0	−0.3	0.0026
30	0.0	0.0	0.0	0.0	−2.4	0.0	−1.6	0.5	0.0006
60	0.0	0.0	0.0	0.0	−1.9	0.0	−0.3	0.7	0.0004
90	0.0	0.0	0.0	0.0	−1.9	0.0	0.7	0.2	0.0004
120	0.0	0.0	0.0	0.0	−2.4	0.0	0.4	−0.5	0.0004
150	0.0	0.0	0.0	0.0	−3.7	0.0	−0.9	−0.8	0.0005
180	0.0	0.0	0.0	0.0	−0.1	0.0	−2.0	−0.3	0.0033
210	0.0	0.0	0.0	0.0	4.5	0.0	−1.9	0.5	0.0121
240	0.0	0.0	0.0	0.0	2.6	0.0	−0.4	0.8	0.0059
270	0.0	0.0	0.0	0.0	1.6	0.0	0.7	0.3	0.0020
300	0.0	0.0	0.0	0.0	3.7	0.0	0.5	−0.5	0.0042
330	0.0	0.0	0.0	0.0	1.4	0.0	−0.9	−0.8	0.0044

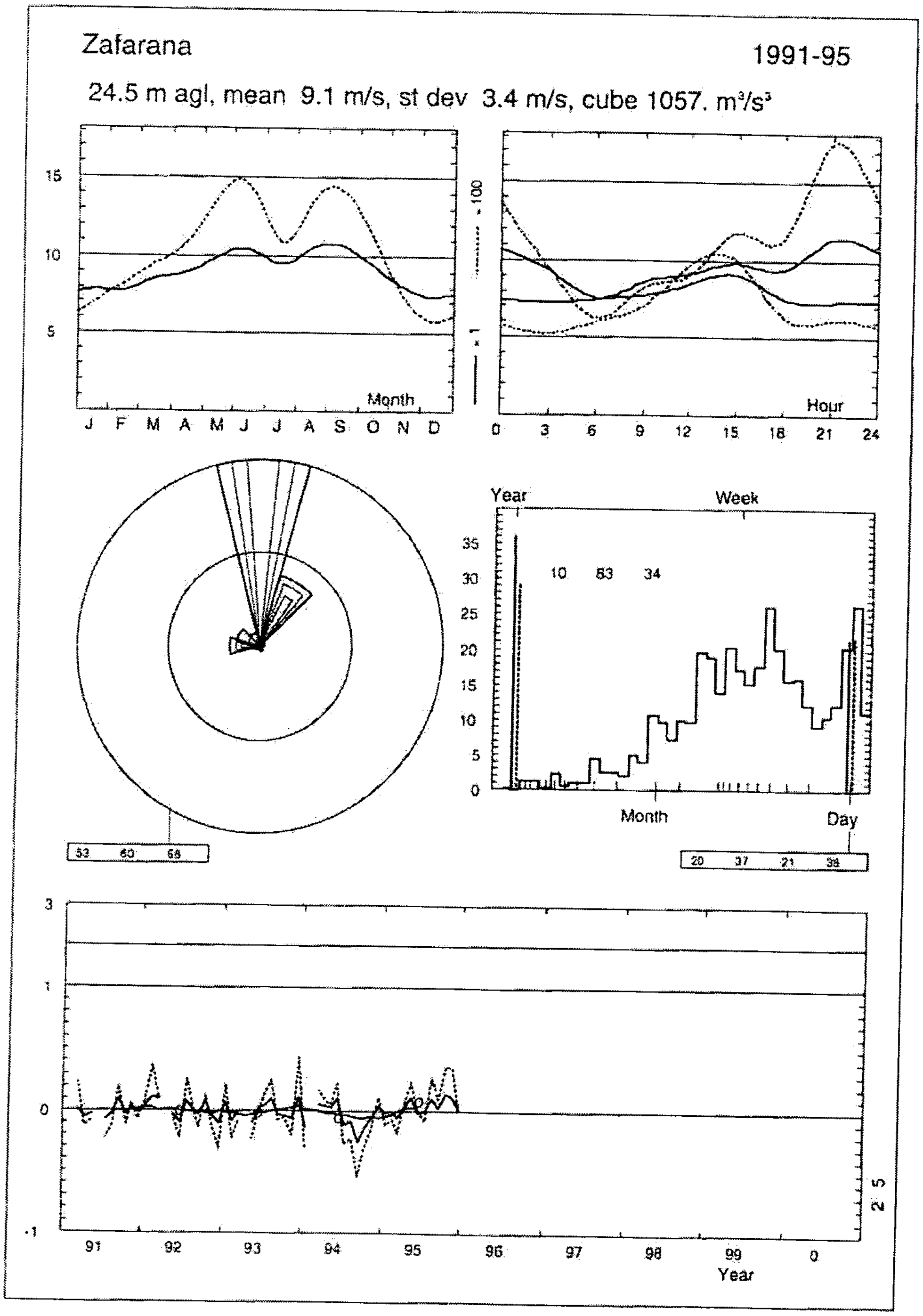
Height of anemometer: 24.5 m a.g.l. 1991 0312 1525–1995 1231 2355

Sect	Freq	<1	2	3	4	5	6	7	8	9	11	13	15	17	>17	*A*	*k*
0	52.6	0	3	5	10	14	24	47	80	112	281	255	128	35	6	11.4	4.21
30	20.7	1	6	13	21	33	51	83	109	131	276	186	71	17	2	10.3	3.78
60	1.7	13	63	130	198	209	164	125	60	25	11	1	0	0	0	5.1	2.62
90	0.8	26	124	219	338	165	72	34	15	1	3	0	2	0	0	3.9	2.31
120	0.8	28	100	179	218	153	99	75	46	23	50	19	7	3	0	4.7	1.51
150	1.7	9	36	64	88	100	85	78	79	80	177	126	61	13	6	8.8	2.39
180	0.8	18	78	109	125	119	88	83	62	63	119	87	30	7	10	7.0	1.71
210	0.3	49	200	191	184	138	98	52	34	19	23	6	2	2	2	4.1	1.53
240	1.5	11	51	69	62	68	76	104	106	105	171	108	49	16	4	8.7	2.53
270	8.7	3	15	31	56	74	93	124	128	115	171	106	54	21	7	9.0	2.49
300	6.7	3	22	69	123	181	214	188	118	48	23	7	3	1	0	6.2	3.04
330	3.7	5	43	122	192	224	183	107	58	29	23	9	3	0	0	5.3	2.28
Total	100.0	2	13	26	42	51	60	76	91	104	229	187	89	24	4	10.3	3.42





	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	7.4	6.9	8.8	9.3	10.5	11.2	10.6	11.3	11.2	9.6	7.6	7.0	9.4
1	7.3	7.1	8.6	8.8	9.7	10.5	10.2	10.8	10.8	9.1	7.6	6.8	9.0
2	7.0	7.2	8.4	8.8	9.7	9.9	9.6	10.3	10.3	8.6	7.5	6.9	8.7
3	7.2	7.4	8.1	8.7	9.3	9.4	9.3	9.9	9.9	8.4	7.1	6.9	8.5
4	7.5	7.4	7.7	8.0	8.6	8.8	8.6	9.3	9.4	8.1	7.1	7.1	8.2
5	7.2	7.2	7.4	8.0	8.4	8.4	8.0	8.8	9.1	7.9	7.1	7.2	7.9
6	7.4	7.5	7.1	7.5	8.3	8.5	7.5	8.3	8.8	7.8	7.4	7.2	7.8
7	7.5	7.7	7.0	7.8	9.0	9.5	8.4	9.6	9.3	7.9	7.4	7.2	8.2
8	7.3	7.8	7.8	8.3	9.4	9.7	8.5	9.9	9.9	9.0	7.7	7.3	8.6
9	7.8	8.3	8.2	8.6	9.4	9.7	8.6	9.9	10.2	9.5	7.9	7.6	8.8
10	7.8	8.3	8.6	8.8	9.6	9.9	8.5	10.0	10.3	9.7	7.8	7.7	9.0
11	8.1	8.3	8.8	9.2	9.9	9.8	8.9	10.0	10.2	9.6	8.3	7.7	9.1
12	8.5	8.3	9.2	9.2	10.0	10.0	9.1	10.2	10.4	9.5	8.5	7.9	9.3
13	8.9	8.3	9.2	9.3	10.0	10.3	9.5	10.4	10.8	9.6	8.6	8.1	9.5
14	9.1	8.9	9.3	9.7	10.1	10.8	9.6	10.8	11.1	9.8	9.1	8.2	9.8
15	9.1	8.4	9.4	9.2	10.4	11.1	9.8	11.2	11.6	10.0	9.1	8.5	9.9
16	9.1	8.9	9.4	9.6	10.5	11.5	9.8	11.3	11.5	9.9	9.0	8.4	9.9
17	8.3	8.3	9.4	9.2	10.7	11.5	9.7	11.3	11.2	9.3	8.0	7.4	9.5
18	7.5	7.5	8.3	8.7	10.3	11.1	9.4	10.7	10.2	9.0	7.6	7.1	9.0
19	7.3	7.0	8.2	8.4	10.1	10.8	9.2	10.4	10.6	9.5	7.8	7.0	9.0
20	7.5	7.4	8.7	9.2	10.9	11.3	10.2	11.4	11.5	10.1	7.8	7.0	9.5
21	7.3	7.5	8.9	9.7	11.4	11.9	11.4	12.2	12.1	10.2	8.0	7.1	9.9
22	7.4	7.5	8.9	10.3	11.4	11.9	11.5	12.4	12.1	9.9	7.9	7.2	10.0
23	7.4	7.4	9.0	9.7	10.9	11.4	11.3	12.0	11.7	9.8	7.8	7.2	9.7
Mean	7.8	7.8	8.5	8.9	10.0	10.4	9.5	10.5	10.6	9.2	7.9	7.4	9.1



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1991	—	—	8.6	8.4	9.7	—	8.8	10.1	11.6	9.0	8.2	7.2	9.1
1992	8.0	8.6	9.3	—	9.6	9.3	10.2	10.5	10.2	10.0	7.6	6.6	9.1
1993	8.3	7.0	8.4	—	8.9	10.6	9.8	11.5	10.3	8.8	7.4	8.2	9.0
1994	6.8	—	9.0	9.2	10.3	11.3	8.4	9.6	7.9	8.0	7.5	7.7	8.8
1995	7.6	7.7	8.0	9.2	11.0	10.3	9.4	11.5	10.9	10.5	8.7	7.5	9.4
Mean	7.8	7.8	8.5	8.9	10.0	10.4	9.5	10.5	10.6	9.2	7.9	7.4	9.1

Roughness Class 0 (z_0 = 0.0002 m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	12.4	10.5	7.6	3.9	4.4	8.5	7.9	5.4	9.3	9.1	6.6	5.8	10.7
	4.48	3.58	2.04	2.14	1.45	2.23	1.95	1.52	2.71	2.66	2.77	2.56	2.97
25	13.5	11.5	8.3	4.3	4.9	9.3	8.6	5.9	10.1	9.9	7.2	6.3	11.7
	4.56	3.67	2.10	2.20	1.50	2.30	2.00	1.57	2.79	2.74	2.86	2.64	3.02
50	14.4	12.3	8.9	4.6	5.2	10.0	9.3	6.3	10.9	10.6	7.7	6.8	12.5
	4.69	3.78	2.16	2.26	1.53	2.35	2.06	1.61	2.86	2.81	2.94	2.71	3.08
100	15.4	13.3	9.7	4.9	5.7	10.8	10.0	6.9	11.8	11.5	8.4	7.4	13.4
	4.60	3.68	2.09	2.19	1.49	2.28	2.00	1.56	2.78	2.73	2.84	2.62	3.05
200	16.8	14.6	10.7	5.5	6.2	11.9	11.0	7.5	13.0	12.7	9.3	8.2	14.7
	4.45	3.52	1.98	2.08	1.41	2.17	1.90	1.48	2.65	2.59	2.69	2.48	2.99
Freq.	48.7	23.3	3.2	0.9	0.8	1.6	0.9	0.4	1.5	7.9	6.7	4.0	100.0

Roughness Class 1 (z_0 = 0.0030 m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	10.4	8.5	4.0	3.1	3.7	7.1	6.3	4.3	7.7	7.4	5.2	5.5	8.9
	3.95	3.07	2.08	1.76	1.20	1.93	1.59	1.30	2.32	2.22	2.69	1.48	2.66
25	11.8	9.7	4.7	3.6	4.4	8.3	7.3	5.0	8.9	8.6	6.1	6.5	10.2
	4.18	3.35	2.29	1.93	1.31	2.11	1.73	1.43	2.53	2.44	2.96	1.63	2.82
50	13.1	11.0	5.3	4.1	5.1	9.4	8.3	5.9	10.1	9.8	6.9	7.5	11.5
	4.56	3.83	2.66	2.24	1.52	2.42	1.97	1.66	2.91	2.82	3.44	1.88	3.07
100	14.9	12.9	6.3	4.9	6.1	11.1	9.8	7.0	11.9	11.6	8.2	8.9	13.2
	4.70	3.84	2.64	2.22	1.51	2.42	1.98	1.64	2.91	2.80	3.41	1.87	3.17
200	17.8	16.2	8.1	6.2	7.7	14.0	12.1	8.8	14.9	14.7	10.4	11.2	16.1
	4.53	3.67	2.52	2.12	1.44	2.31	1.89	1.57	2.78	2.67	3.25	1.78	3.17
Freq.	52.2	20.2	1.7	0.8	0.8	1.7	0.8	0.4	1.8	8.5	6.5	4.7	100.0

Roughness Class 2 (z_0 = 0.0300 m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	8.7	7.1	3.3	2.6	3.6	5.9	5.2	4.7	6.3	6.0	4.4	7.6	7.5
	3.90	3.01	2.05	1.56	1.19	1.89	1.55	1.53	2.28	2.13	2.63	2.81	2.73
25	10.2	8.4	4.0	3.2	4.4	7.1	6.2	5.7	7.6	7.2	5.2	8.9	8.9
	4.08	3.23	2.21	1.68	1.28	2.03	1.66	1.65	2.45	2.30	2.84	2.97	2.86
50	11.5	9.6	4.6	3.7	5.2	8.2	7.2	6.6	8.7	8.3	6.0	10.1	10.1
	4.36	3.59	2.49	1.88	1.44	2.26	1.84	1.85	2.74	2.58	3.19	3.24	3.07
100	13.2	11.3	5.5	4.4	6.2	9.7	8.5	7.8	10.3	9.9	7.1	11.7	11.7
	4.69	3.84	2.65	2.01	1.53	2.42	1.97	1.98	2.92	2.75	3.40	3.47	3.28
200	15.6	13.9	6.8	5.5	7.6	11.9	10.4	9.7	12.8	12.3	8.9	14.1	14.1
	4.53	3.67	2.53	1.92	1.46	2.31	1.88	1.88	2.80	2.63	3.24	3.34	3.26
Freq.	48.5	18.0	1.5	0.8	0.9	1.6	0.8	0.5	2.6	8.3	6.2	10.4	100.0

Roughness Class 3 (z_0 = 0.1000 m)

z	0	30	60	90	120	150	180	210	240	270	300	330	Total
10	7.5	6.1	2.9	2.4	3.4	5.1	4.4	4.5	5.5	5.1	3.8	7.0	6.6
	3.85	3.00	1.97	1.57	1.26	1.87	1.53	1.70	2.26	2.05	2.56	3.28	2.75
25	9.1	7.5	3.5	3.0	4.3	6.3	5.5	5.6	6.8	6.3	4.7	8.5	8.0
	4.01	3.19	2.11	1.68	1.34	1.99	1.63	1.82	2.42	2.20	2.74	3.44	2.87
50	10.5	8.7	4.2	3.5	5.1	7.4	6.4	6.6	7.9	7.4	5.5	9.8	9.3
	4.26	3.51	2.33	1.86	1.48	2.19	1.78	2.01	2.67	2.43	3.03	3.69	3.05
100	12.1	10.3	4.9	4.2	6.2	8.8	7.7	7.8	9.4	8.8	6.5	11.3	10.8
	4.67	3.85	2.57	2.04	1.62	2.40	1.96	2.21	2.94	2.67	3.33	4.05	3.30
200	14.3	12.6	6.1	5.2	7.6	10.8	9.3	9.6	11.5	10.8	8.0	13.6	12.9
	4.52	3.69	2.45	1.96	1.55	2.30	1.88	2.12	2.81	2.56	3.19	3.90	3.28
Freq.	46.0	16.5	1.5	0.8	1.0	1.5	0.7	0.6	3.2	8.1	5.9	14.2	100.0

z	Class 0		Class 1		Class 2		Class 3	
m	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}
10	9.6	754	8.0	465	6.7	274	5.8	180
25	10.4	973	9.1	675	7.9	444	7.1	321
50	11.2	1178	10.2	914	9.1	634	8.3	483
100	12.0	1475	11.9	1390	10.5	958	9.7	742
200	13.1	1934	14.4	2490	12.6	1665	11.6	1281