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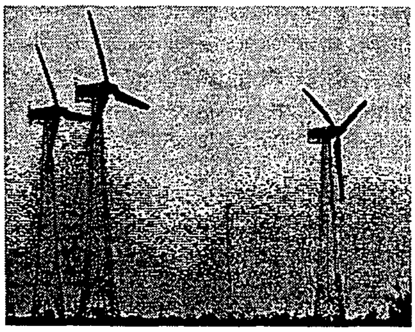
PROGRESS IN WIND ENERGY UTILIZATION

Bent Sørensen



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PROGRESS IN WIND ENERGY UTILIZATION

by Bent Sørensen

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ABSTRACT:

The paper gives a review of the current status of wind energy technology and presents analysis of economic and environmental implications of wind energy systems. The history of wind energy is traced back to the Mediteranean and Persian areas, and new theories of the transfer of wind technology are presented. Finally, the present picture of installed capacity and policy is given.

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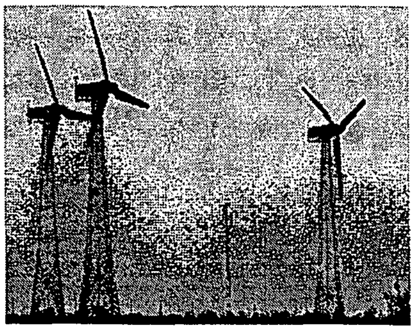

PROGRESS IN WIND ENERGY UTILIZATION

CONTENTS

STATUS 1995

The new interest in wind energy over the last 20 years has seen a very successful development of commercial wind turbines of increasing unit size, with the present generation ranging from 500 kW to 1 MW. From a technical perspective, these windmills taken together have proven a long working life, allowing long-term maintenance contracts and commercial insurance to be issued at favorable terms. Also from an economic point of view, the development has been successful, in that new wind turbines at windy locations today are competitive with coal power generation, even at current low coal prices, and without even considering environmental benefits. The present cost calculations are illustrated in Table 1, based on a 500 kW Vestas turbine. The kWh cost is more than three times lower than it was 20 years ago, in real terms.

Table 1. Economy of current wind technology

Capital costs (per unit of rated power)(a):	
Turbine capital cost installed	6000 DKr/kW (about 800 ecu or 1000 US$)
Typical foundation costs	300 DKr/kW (about 40 ecu or 50 US$)
Typical grid connection costs	100 DKr/kW (about 33 ecu or 17 US$)
Running costs (totalling 2% of capital cost annually)(b):	
Insurance costs	40 DKr/kW/y (about 5 ecu or 7 US$)
Service contract	25 DKr/kW/y (about 3 ecu or 4 US$)
Other O&M costs, etc.	55 DKr/kW/y (about 7 ecu or 9 US$)
Assumed cost of capital(c)	10%/y
Assumed capacity factor(d)	35%
Implied cost of power	0.25 DKr/kWh (about 0.032 ecu or 0.04 US$)

(a) Windmill Price List, Danish Technological Institute, October 1994

(b) Skriver, S, 1994. Economic Analysis of Windmills (in Danish), Naturlig Energi, Nov. and Dec. 1994, pp. 12-14

(c) Typical Danish 1994 value for private investor's loan financing

(d) Based on (a): 3066 KWh/y per kW(rated power), corresponding to a prime location in Denmark

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The sensitivity analysis shown in Figure 1 indicates, that the most important factors influencing the cost of power produced from the wind are wind resources and cost of capital. Wind resources are dealt with in a following chapter. The capacity factor (average produced power over rated power) used in Table 1 corresponds to a good coastal site in Denmark, which is also near the top of European sites, although not as good as the Western coasts of Scotland or Ireland. In the interior of Denmark, and on many other locations in Europe and the World, a typical capacity factor would be 20-25%, and the cost of power correspondingly higher. On the other hand, further cost reductions are expected for the turbines being produced over the next decade.

The other important factor, the cost of capital, is determined in part by economic climate in general, and in part by particular financing schemes pertaining to wind power investments. The figure used in Table 1 is typical of the financing currently available to average citizens wishing to erect a windmill of buy a share in a shared installation. Most power utilities have access to financing at a lower interest rate. On the contrary, private investors just four years ago paid 17% on similar loans, reflecting the economic uncertainty prevailing at the time. Average interest rates over the 20th century have been roughly 3% over inflation, which currently would mean 5% total interest rate in Denmark. The value of 10% assumed in Table 1 is thus a conservative estimate when viewed in a longer historical perspective, but a low one when viewed in a shorter perspective.

Remaining parameters such as operation and maintenance costs, and turbine life-time are less uncertain, and the capital costs fluctuate little between manufacturers, but are expected to continue to exhibit a declining trend with time and with turbine unit size. Turbines exported used to be on average slightly more expensive than locally produced ones, due to transportation and in some cases lack of a company base in the recipient country, but export prices have approached the local prices more and more. For example, the average Danish 1993 export cost was 7.5 DKr/W as compared with the 6 DKr/W quoted in Table 1, but exports included many smaller sized turbines (1).

The installed power in different parts of the World is summarized in Table 2, and the development in time of the total stock is illustrated in Figure 2. Figure 3 gives the average unit size of turbines installed in Denmark in a particular year and the specific power production. Clearly the increase in unit size has increased specific production, for reasons discussed below.

Table 2. End-of-1994 installed wind power worldwide

World	**3930 MW**
Europe	**1819 MW**
Denmark	510
Germany	510
UK	300
Netherlands	200
Spain	90
Greece	50
Italy	40
Sweden	38
Portugal	20
France	14
Belgium	10
Ireland	10
Norway	9
Finland	8
Poland	5

Czech Republic	4
other	1
North America	**1793 MW**
USA	1755
Canada	38
Latin America	**50 MW**
Asia	**211 MW**
India	120
China	60
Israel	6
other	25
Africa	**37 MW**
Egypt	33
other	4
Australia & Pacific	**20 MW**

sources: (a) Møller, T, 1994. Naturlig Energi, september, p. 6, with estimated corrections.
(b) Nielsen, P, 1993. Energi- og Miljødata, 3. kv., p. 1-2

Just over 50% of the worldwide windmill stock has been manufactured in Denmark. the rest chiefly in the USA, Germany, England, Holland, Belgium, Japan and Italy. However, the industry structure has been changing in recent years, such that e.g. a considerable number of the Danish manufacturers are presently owned by international investment consortia.

Summing up government plans for wind power expansion, it seems that the installed stock by year 2000 will reach 9 GW (1). About a decade ago, the strongest expansion was in California, financed chiefly by tax evasion schemes, but present plans are most significant in Europe and Asia, and justified mainly as instruments of greenhouse emission reduction.

Figure 3 shows the gradual increase in unit size and the increase in specific power production, for Danish locations. Tower heights have increased less than rotor diameters, but part of the specific power increase is still due to higher winds experienced at elevated hub heights. Another contributor is the improved wind sites selected for windmills in Denmark. The average potential production at the selected sites increased by 25% from 1980 to 1986, but has been constant since (2). The explanation is probably that early windmills were erected at the owner's farm, while recent mills of shared ownership (typically 100-200 share holders) or utility ownership are placed more freely at the best locations, implying better wind conditions. The cessation after 1986 of the site improvement may mean that the best available sites have now been taken. Strict environmental siting criteria prevents the use of coastlines, but in the future, off-shore windmills are expected to play an increasing role. Present off-shore wind farms (see Figure 8d) are situated 2-4 km from the coastline and thus cause very little visual intrusion. The cost penalty for off-shore foundation work and sea cables presently increase the turbine price by about 80%, which is not compensated by the improved wind resource. However, when the off-shore siting becomes more of a standard operation, the price is expected to drop considerably.

BRIEF HISTORY OF WIND ENERGY UTILIZATION

As a renewable energy source directly available to man in most parts of the world, wind energy has played an important role throughout human history. Wind energy has provided the ventilation needed to sustain use the combustion of e.g. firewood in a way that brought in new oxygen supply and preserved an acceptable level of air quality, also when cooking became an indoor activity. Persian chimneys invented several hundred years ago used a wind flow to drive air over a body of water, causing evaporative cooling and thus air-conditioning the rooms through which the air flow was pulled by the suction provided by the wind at the chimney. In most parts of the world today, infiltration of fresh air into buildings is controlled by wind rather than by mechanical systems, and wind is furthermore serving an important role in dispersion and dilution of pollutants, e.g. by use of stacks extending into the wind for emission release.

Active use of wind for energy supply purposes is believed to have started earlier than 5000 years ago in the Mediterranean region, when wind propulsion by sail-ships is first documented (3), cf. Figure 4a. New types of merchant and war ships were developed by the greek about 550 BC and advanced by the romans during the first centuries AC (4). Hydrodynamically optimized boat shapes were used by the Vikings of Northern Europe 600-800 AC. The development of wind-driven ships continued to advance with the Flemish and Portuguese ships refined from the Roman types. It is with such ships (Figure 4b), that the Europeans colonized several continents (4). The use of large sail-ships continues over the following centuries, until about a hundred years ago (Figure 4c), when diesel engine driven ships take over. Sail-ships continue to play a role for leisure boats, and from time to time, there have been attempts to develop fuel-saving combined sail and engine concepts for large ships (5).

Possibly the earliest mention of windmills dates back to about 400 BC, where a Hindu book called "Arthasastra of Kantilya" suggests the use of windmills for pumping water (6), but no other evidence seems to support this claim. Toy-like applications are the wind-powered organ (Figure 5a) described in the first century AC by Heron of Alexandria (7,8), or the wind-driven Buddhist prayer-wheels mentioned around 400 AC (9). Heron replaced the blowing source for a pipe-organ invented by Ktesibios a few hundred years earlier, by what appears to be a horizontal axis wind turbine. Heron's idea to reverse the action of already well known fans did not lead to wind turbine applications right away, but is speculated to have influenced the transition from vertical-axis to horizontal-axis machines in Europe several hundred years later (10). The suggestion often made in the literature, based on (9), that the drawings in Heron's book are added later by someone familiar with wind turbines, is clearly false, as a multitude of existing copies of Heron's book were produced several hundred years before either Eastern or Western type windmills became known (11).

Evidence for concrete development of vertical axis windmills for grinding (but also for irrigation and rice pounding) is found in Persia during the late part of the first millenium. An application for powering a water fountain is hinted at in 800 AC (12). Two sources from the early 10th century (13,14) suggest that windmills were first proposed by Abu Lulua in 644, and developed sometime during the two following centuries, as a direct continuation of the technique in use for hand-milling and milling by water wheels (10,15). The mill-stones were even placed above the rotor blades, that were made of cloth, as evidenced by the first known drawing of a Persian windmill (Figure 5b), dating from the late 13th century (16). This arrangement was convenient for a low-head water-wheel, but it was later realized, that placing the rotor above the mill stones offered a better solution in the wind case, both in terms of efficiency and of convenience for the miller's work (cf. the Persian windmills found in the Sistan region early in this century (15)). Persian style mills have been found on Sumatra in 1154 (17) and in India in the 14th century, suggesting a gradual dissemination eastwards. Lewis (10) speculates that the abundance of mills in the region deriving from the state of Bactria, created by Alexander the Great, populated by many Greek emigrants, and existing independent of Greece and Rome from about 200 BC to 200 AC, could point to a common denominator for the development of wind energy. This speculation would assume that perhaps the ideas of Heron were further developed by the greek emigrants and first put to practical use in the Sistan region of Persia, known for its steady and strong winds during three months of the year.

The horizontal axis windmill first appears in Europe, and is primarily used for cereal grinding but also for water pumping and in the Netherlands for drainage. It is considerably more efficient than the vertical axis machines of Persia. The first description of the new concept is in a French tax announcement from 1105, and the earliest picture of this type of windmill is in the 1180 Canterbury windmill psalter (Figure 5c) (18). Speculation suggests that the Persian concept was transmitted to Europe by the technicians accompanying the crusaders to the Middle East, but that European developers added the idea of a horizontal to vertical shaft transmission, which would long be known to them, e.g. from the gear drive of the Vitruvian waterwheel introduced during the first century BC (19). However, a perhaps more likely suggestion is that of "stimulus diffusion". i.e. that the Jerusalem travellers just related back home, that it could be done, and that European entrepreneurs then made the detailed design of the windmill and incorporated their knowledge of gear mechanisms.

Attempts at finding a road of gradual dissemination from Persia to Europe have considered at least two routes: One leading through Constantinoble to the greek islands and on to western parts of the Mediterranean including Portugal. Along this route one finds some vertical axis turbines of a design similar to the Persian one (one on Karpathos) and a further development of it (1486 in Kandia on Crete, see Figure 5d), but also an abundance of tower mills, i.e. horizontal axis turbines mounted on a tower, sometimes with the possibility of yawing the top. The other route goes through Russian provinces, and comprises horizontal axis mills. Some of the early ones had the mill-stones above the rotor, and in later models, the entire construction could be turned by a lever, albeit with a considerable effort. The similar models (sometimes called post-mills) found further along the suggested route, in Flandern and the surrounding countries, are more advanced in that they use a pivoting design that required much less force. Figure 5c shows a post-mill and Figure 7a a tower mill.

In any case, the horizontal axis windmills soon came into very widespread use, starting in the triangle Normandy-England-Belgium, but soon spreading to Holland, Germany and Denmark (20). Figure 7b shows a Dutch windmill from 1658. These often quite large windmills became abundant in most of Europe, often placed around cities, and used for grinding and irrigation, as well as drainage of low countries. By the end of the 19th century, the efficiency of these mills had increased from the 1% level to around 5% (cf. Figure 12b). In addition to the dominant type, one finds early examples of nearly all alternative designs known today including vertical axis tower (Figure 6a), self-starting Savonius (Figure 6b), hinged vertical blades (Figure 6c; recently reconsidered in the UK (21)) and tornado types (reconsidered from time to time (22), but never successfully). Rotors built into walls as the Sistan mills have been reconsidered (23), but they would not be very efficient. For pumping and irrigation, the American multiblade design came into widespread use during the 19th century (Figure 7c). It is a low-efficiency mill, but one that will start at very low winds (1-2 m/s). New designs developed in the 20th century include Darrieus machines (24)(Figure 6d) and blades with tip-vanes (25)(Figure 8b). They could match or surpass the horizontal axis machines in efficiency, but have never sufficiently attracted manufacturers.

The development of wind turbines for power generation started about 100 years ago, in countries such as Denmark, England, Germany and the United States (26). Serious work on wind turbine efficiency and the aerodynamics of blade performance had been initiated in England in the 18th century and continued in France through the 19th century (27). Systematic airfoil studies began in Denmark 1892, with la Cour's wind tunnel and experimental windmills at Askov Highschool (28). Along with pioneers in the USA (26), his mills were the first to produce electricity. His goal was rural electrification, and the electric power produced by one of his experimental mills was used for electrolysis, generating hydrogen piped to lamps in an adjacent building. The design of aerodynamically efficient rotor blades soon advanced according to the theoretical principles developed for the infant airplane industry. During the following two decades, wind and coal-based electricity were competing fiercely for the Danish market, and it was not until the 1920ies, that fuel-based power became cheap enough to force wind power out of the market, except for small islands. Also in countries such as Switzerland, isolated mountain settlements used windmills in the early 20th century, as did farmers in areas far from the grid. Wind-diesel combinations are again towards the end of the 20th century being increasingly popular in areas far from the grid (29).

World War II again saw a number of windmills produced and erected in countries cut-off from their traditional sources of fuel-supply, such as Denmark. This new generation of wind turbines had concrete tower constructions, but were still DC producers feeding into DC grids. Only after another fuel supply problem, the Suez crisis in 1957, did the Danish engineer Juul experiment with AC production based on wind-driven induction generators (30). His demonstration project, the 200 kW Gedser mill shown in Figure 7d, became the prototype for the new generation of windmills put into production following another oil-supply crisis in 1973-74. While several other countries experimented with megawatt size wind turbines (projects that all failed), the Danish manufacturers started in 1975 with models of modest rating (15 to 30 kW, see Figure 8a) and soon had a blooming business and a fairly good track-record in terms of reliability and power production (31). The industry then chose to gradually increase unit size, a trend which has continued right through to the present models rated at about 1 megawatt (Figure 3). Advanced glass fibre and composite materials have been introduced for the blades, and towers are today often made of steel tubes.

WIND RESOURCE

Winds are caused by differential heating of the atmosphere, in combination with the Earth's rotation and friction within the atmosphere and between the atmosphere and the surface of the Earth. Lorenz has estimated (32) that about 1200 TW on average is used to sustain the general circulation, which is under one percent of the incoming solar radiation. The kinetic energy in the circulation is 750 EJ, so the turnover time is around 8 days (33,34). About half the energy is dissipated in the upper atmosphere, the rest near the surface. As only 3 TW are estimated to be used to create waves (35), land surfaces are responsible for most of the friction. Placing wind turbines near the ground helps this process. If windmills are placed at "good wind sites", this amounts to increasing the roughness of the surface, whereas at other locations, the windmills could be "replacing" other features creating roughness in the surface. One may then ask, what the effect would be of extracting power corresponding to a large fraction of the energy influx that maintains the circulation. The details of these mechanisms are currently under study, but one would think, that if wind turbines causes the average friction to increase substantially at the ground, then the apparent low-altitude wind speeds would become lower, although the gradient further up in the atmosphere might be stronger, because the stratospheric jet streams are unlikely to change. Ultimately the effect might be that more of the atmosphere will follow the Earth's rotation, and hence that significant impacts on global circulation and derived effects could entail.

In any case, even if the entire world electricity use were covered by wind, that would at present be of the order of one TW on average, and hence it is very unlikely that any effect on the global circulation would be felt. In other words, the general resource availability is huge, and the real question is, how much of this resource mankind could harvest in a convenient way, and of course, how the resources are geographically distributed, as compared to the power demand.

The winds at a particular location on the Earth's surface are determined by the geostrophic wind aloft, and the roughness of the terrain (34). The geostrophic winds follow regular patterns determined by the mid-latitude jet-streams and the Equatorial trade winds (see Figure 9), but overlayed with the patterns of short-term weather systems. The roughness is generally high for uneven topography, including the built environment, and low for flat plains and open sea (34). Based on cartological information on topography and measured geostrophic winds, wind maps have been constructed, e.g. for Europe and the USA (36,37). These maps divide the land into areas with average wind speeds in given intervals. It should be said, that the wind map method is very reliable for predicting wind turbine production in fairly flat and uniform areas (In Denmark, manufacturers even give a production guarantee based upon wind map estimates), but cannot be considered very accurate for more complex terrain, e.g. mountain passes and valleys. Furthermore, as the wind turbine power production depends on the third power of wind speed, use of average wind speeds can lead to erroneous estimates, as averages may cover a variety of different underlying distributions. Table 3 gives estimates of exploitable wind resources on land areas, based on the wind maps, but folded with considerations of avoiding conflicts with other land uses. Only sites with an average wind speed exceeding 5.1 m/s at 10m height have been included, and a fairly arbitrary measure of environmental concerns are considered (chiefly visual intrusion). The exploitable potential is over 5 times the current rate of electricity use, but with a distribution substantially different from that of demand.

Table 3. Estimate of wind power potential, including technical and environmental constraints (average possible production in GW).

World	**6050**
Africa	1200
Australia	330
North America	1600
Latin America	610
Western Europa	550
Eastern Europe and former SU	1200
Rest of Asia	560

Based on
(a) van Wijk, AJM, Coelingh, JP, Turkenburg, WC, 1993. Wind Energy. Ch. 3 in Renewable Energy Resources. London: World Energy Conference.
(b) Grubb, M & Meyer, N, 1993. Wind Energy: Resources,systems, and regional strategies, pp. 157-212 in Renewable Energy Sources for Fuel and Electricity, eds: T. Johansson et al., Washington: Island Press

The average height profile of wind speeds at a particular location depends on the stability of the atmosphere. A simple eddy diffusion model predicts a logarithmic height profile, where the height is scaled by the roughness parameter and the velocity by an atmospheric stability parameter (34). The variations in wind speed depends on passing weather front systems, on heating by sunlight, and on a short time scale on stability (gustiness). Figure 10 exhibits clear peaks in the variance spectrum corresponding to the mentioned periods. Seasonal variations of the power in the wind vary with location, as illustrated in Figure 11, and in countries like Denmark has a variation that is anticorrelated with that of solar radiation (38).

WIND ENERGY TECHNOLOGY

The present generation of windmills is characterized by advanced aerodynamical shape of blades, by use of highly advanced materials in blade construction, and by state of the art conditioning and control equipment. The manufacturing process has become very specialized, with some companies concentrating on blades or controls, while tower design and gear mechanisms are manufactured by separate other companies. Only the more mundane parts, such as foundation and site work, are left to local contractors. To some extent, the name-label windmill manufacturer has become just the assembling specialist.

A state of the art turbine presently would have three aerodynamically shaped blades of length 20-30m, made of glass fibre or carbon fibers, a steel tube tower of height 40-60m. The blade profile is optimized for a design wind speed by three-dimensional modelling (34) and verified in wind tunnel tests. Different fixed profiles will make different compromises between maximum power at the design wind speed and high performance at other wind speeds. While differential adjustment of blade shape is not feasible, rotation of the entire blade is a feature of some turbines. This setup is still optimized at one particular wind speed. but the penalty at other speeds can be reduced by rotating the existing profile to the angle giving the best average performance. Most manufacturers do not add this feature, claiming that the cost of being able to adjust blade angles is not recovered by the modest increase in output. For a fixed blade profile, the effect of an increasing wind speed will eventually be the creating of turbulent eddies near the blade, and the corresponding loss of lift force (34). This constitutes what is termed "stall regulation", as it implies that overall power production as function of wind speed will reach a maximum and then stay constant or decline (Figure 12a), and thus eliminate any danger of "running away", i.e. the rotation speed increase that in the past caused failure of many American multiblade windmills. Stall regulation also means that if the connection to the grid is lost, then the wind turbine will not increase its rotational speed uncontrollably, but will stay at a constant speed, from which it may be brought to a halt by conventional brake technology.

The choice of three blades has to do with stability and lifetime of the blades. Conventional blade theory ignoring interference phenomena (as first proposed by Betz in 1926 (39)) would predict a slight gain from more blades, but the economic optimum would rather be two blades. In actuality, rotors with few blades may have difficulties, as the blades experience quite different wind regimes (say if they are separated by 25m), and there is the further interaction of wind flows around blades with the tower, all of which disfavors at least the two-blade solution in terms of stress and hence blade life (40). This lesson has been learned in practice from two-bladed constructions such as the US MOD-2 (Figure 8c), viz-a-viz three-bladed constructions of the same size (41). Overall efficiencies for leading technologies over time is depicted in Figure 12b, where the efficiency parameter C_p is also explained. Simple axial flow calculations first made by Betz (42) indicate a maximum C_p of 16/27 or about 59%. This may be exceeded by turbines generating a rotational or axial flow, such as ducted rotors or the tip-vane concept mentioned earlier (cf. 34).

The favored electricity generator with current machines is the induction generator, which operates at near-constant rotational speeds and allows the AC grid to maintain the correct frequency without active controls (this concept was already used for the first AC grid-connected windmills around 1920 (43)). However, a few machines presently use synchronous generators, which allow varying speeds and hence a somewhat better average efficiency. It is estimated, that most manufacturers will shift to synchronous generators with advanced computer control over the next 5-15 years.

The world market success of Danish wind generators owes a great deal to the excellent quality control offered by the Danish Windmill Test Station. This started as an idea offered by four unemployed engineers in the late 1970ies, and received government support under an unemployment programme focussing on furthering innovative ideas, that existed at the time. Once the wind test station had proven successful, it was incorporated into the Risø National Laboratory. The test station not only offers tests and certification, but has closely collaborated with the manufacturers in improving their designs. This collaboration has run exceptionally smoothly, to the benefit of the industry, and surprisingly without friction due to competitive concerns.

ENVIRONMENTAL IMPACTS AND LIFE-CYCLE COSTS

The impacts of an energy technology may be divided between the stages of equipment manufacture and installation, the productive operation of the plant, and finally the decommissioning process. As with many renewable energy technologies, wind energy is expected to have a considerable fraction of its impacts during the manufacturing stage, where the bulk part of economic expenditure, environmental effects of materials procurement, and hazards of industrial work environments is concentrated. On the other hand, these are impacts well known from other types of industries, and hence fairly accurate assessments can readily be made. The same is true for the operational phase, where impacts are again similar to those of familiar enterprises. As for final disposal of equipment, there are no long-term effects to consider (such as radioactivity in the case of nuclear power plants), but only the dismantling and disposal or recycling of materials.

Detailed environmental analyses of wind energy were first made around 1980 (44), singling out safety hazards during construction and maintenance, the risk of parts such as blades being expelled in case of failure, impacts of noise and electromagnetic interference, risk presented to birds in the area, visual intrusion and climatic impacts, due to the redistribution of energy flows near the turbine.

Recent estimates of the environmental impacts from wind turbine construction are summarized in Table 4. The underlying calculations are top-down estimates, based upon energy imbedded in materials and used in manufacture, per unit of capital outlay or per unit of materials' weight. Emissions are derived from existing data on average emissions from the production of the different types of energy assumed to be used in wind turbine manufacture. Finally, the emissions are distributed over the power production of the turbine, assuming a 20 year lifetime. The slight differences in emissions quoted are consistent with differences in fuel mix in the three countries considered (UK, Denmark, Germany).

Table 4. Energy input to and emissions from manufacture and operation of wind turbines.

	Turbine manufacture			O&M	total
	(a)	(b)	(c)	(d)	(e)
energy inputs (GJ/kW rated)	-	-	6.6	2.2	8.8
energy ratio (20y outputs/inputs)	-	-	-	-	18
energy payback time (y)	-	-	0.8	0.3	1.1

carbon dioxide (g/kWh)	9.1	11	12.1	3.8	15.9
sulphur dioxide (g/kWh)	0.087	$<$ 0.05	0.05	0.01	0.06
nitrogen oxides (g/kWh)	0.036	$<$ 0.05	0.04	0.02	0.06

(a) N. Eyre (54)
(b) U. Fritsche, 1993. TEMIS, pp. 103-111 in Life-cycle Analysis of Energy Systems, Paris: OECD
(c) The energy ratio and payback are calculated on the basis of data furnished in H. Meyer et al, 1994. Risø Report R-770(DA), from which the emissions (c) are directly taken.
(d) Total O&M energy input is given for the assumed 20y operation period, based on data from Meyer et al., cited above in (c).
(e) Sum of (c) and (d), i.e. total lifecycle estimates except for energy used for decommissioning, which is not estimated.

Other potential impacts during manufacture are connected with the use of toxic materials, and particularly chemicals used in the production of glass fibre blades (epoxy resins, acids, etc.). Modern production facilities employ such chemicals in sealed environments without human access, and with maximum recycling of residuals (44). Thus occupational exposure as well as environmental emissions are primarily associated with accidents. No statistics on accidents specific to the blade manufacturing industry are available, but data from similar industries suggest risks of very small magnitude.

The occupational hazards associated with erection of turbines, as well as subsequent repair work, are similar to those of the building and construction industry occupied with high-rise buildings, bridges etc. As turbine sizes have increased, concrete tower constructions have been phased out in favor of steel tube towers, that usually consist of quite large prefabricated parts needing only simple assembly on site. Most access to the nacelle during construction as well as maintenance is thus involving inside stairs and only in case of blade work may mounting by crane or stepping out from the nacelle be required. A Swiss study by Fritzsche looks at accidental deaths during manufacture and construction, presumably of fairly small wind turbines, plus public road accidents involving transported wind turbine equipment (45). Occupational injuries calculated more recently from average UK statistical data for the mechanic and electric engineering industries, and for the construction sector, lead to accidental death rates some 4 times lower than the Swiss estimate, when applied to the wind turbine manufacture on the basis of value added. The new data on death and injury are summarized in Table 5. To this should be added any economic loss. Statistics on outage and component failure indicate, that some 10% of operating turbines experience a component failure in a given month, and it is usually corrected in a day or two. Only 4% of the failures result in replacing the component, and around 0.2% may exhibit a safety risk such as a blade broken off (31). The risk to the public arising from expelled blades is estimated as negligible (46).

Table 5. Accident risks associated with windmill manufacture and erection, for a power production of 10^{12} kWh (a)

	Materials & manufacture	Construction	Operation
Deaths	5	20	(*)
Injuries with hospitalization	400	540	
Minor injuries	2800	2600	

(a) N. Eyre (58)
(*) In addition to the injuries quoted, Eyre estimates road accidents for construction and maintenance workers, which if included would roughly double the values given. However, the estimates are admitted to be too high, based e.g. on 4 independent maintenance visits a day to a 100 windmill farm from a base 50 km away.

Land use by wind turbines are estimated as $10m^2$ per kW rated power (47). This takes into account, that wind turbine siting is only allowed in non-urban zones, and that activities such as agriculture is possible very close to the turbine. The main part of the land area use is for access roads allowing maintenance crews to drive up to the rotor. Visual intrusion has been studied by several authors. It depends on the technology used (e.g. steel truss towers or tubular towers) and on the density and layout of turbines (wind farms or individual, dispersed units). It also depends on ownership, as e.g. the share-financed windmills in Denmark (for which legal requirements include nearness of owners and correspondence between share size and electricity use) are considered positive contribution to the landscape, while utility-owned windmills erected without participation of the local population in some cases have induced protests (although mainly from individuals employed in the fossil fuel sector). Consumer surveys have shown very positive attitudes to both present and planned levels of windmill penetration: 83% of the population wants an increased effort to expand wind power in Denmark, while only 8% are against (48). Efforts by architects to design wind farms with attractive layout and integration into surroundings have played a role in achieving the acceptance of visual impacts (49). There are other locations (e.g. in California), where wind farms have been installed without considerations of the best visual integration.

Noise from wind turbines are of two kinds. One is the noise from gear-box and transmission, which can be reduced to arbitrary small environmental values by sound insulation of the nacelle. The other is the aerodynamical noise from the wind flow being shedded off the wing blades. This cannot be arbitrarily reduced, as it is the same type of environmental noise created by trees or buildings. It will necessarily increase with increasing wind speed. To regulate aerodynamical noise, the blade profiles or rotational speeds of the rotor will have to be changed, which may not be compatible with the optimization of energy collection and choice of control strategy. For instance, the stall regulation described in the preceding section create eddies and hence noise around the blades in high winds, and to allow either increased rotation or minimal intrusion incident angle may create other problems. Noise from air flow around the tower or due to blade-tower interaction can be minimized by proper choice of tower construction and rotor separation from tower. Smooth tubular towers generally create much less noise than steel truss towers. Typically, one must thus expect a noise level, which at wind speeds below the break-in speed increases with wind speed, then a fairly constant noise level during operation near the design wind speed, and finally an increasing noise level in the high--wind stall region (44).

The basic frequency of rotor noise is linked to the rotational frequency (typically of the order of 0.3 Hz) and its harmonics. Transmission noise has a higher base frequency but may as mentioned be dealt with by insulation. Harmonics of the rotor frequency, as well as new frequencies created by interaction with environmental objects, may have components in the audible frequency region, which significantly exceeds the background level at distances within a few rotor diameters from the turbine. Of course there can be substantial temporal variations in the directional pattern, and the turbine may occasionally be heard up to around 25 rotor diameters away. Measurements show an increase in noise level of about 10 dB(A), at rated turbine output and measured two rotor diameters away from the turbine, due to aerodynamical noise from the blades (50,51). dB(A) is a logarithmic scale with a frequency averaging believed to represent human noise perception in an average fashion. Noise profiles are in many countries routinely measured at each new, significant wind installation.

Human annoyance by noise depends on several qualities such as tonality, intermittency, background level, activity (e.g. sleep) and personal sensitivity. A study by Keast (52) finds that the percentage of people annoyed by levels between 40 and 50 dB(A) ranges from zero to 3%, those annoyed by noise in the interval 50-60 dB(A) ranges from zero to 15%, for the interval 60-70 dB(A) from 3 to 33%, for 70-80 dB(A) from 20 to 60%, and finally for the interval 80-90 dB(A) from 35 to 90%. Regulatory limits for the general public range from 70 dB(A) in industrial areas to 35 dB(A) at night in residential and recreational areas (53). For infrasound (0.1-5.0 Hz), regulatory limits of 70 dB(A) exists (51,54). Several models are available to calculate the propagation of sound, resulting in predicted noise levels at specified locations, as function of sound source locations and strengths (55,56). Ground absorption must be considered in such models in order for the predictions to agree with measurements (57). In complex terrain the models tend to be fairly inaccurate, but for typical wind turbine sites modelling can provide a fair estimate of the combined noise impact at inhabited locations in the neighborhood of the turbine(s)(58). For a 103 times 250kW-turbine wind farm in Wales, the noise level increments are found to reach occasional maxima of 3.4 dB(A) at a nearby house, below 2.0 dB(A) at any location 2km from the wind farm, and 0.05 dB(A) at the nearest village, 3.5km away. These are outdoor levels, considerably reduced inside any building.

Telecommunications interference has been thoroughly discussed (59). Like other structures a windmill reflects electromagnetic radiation in a way that depends on the materials used (large scattering cross section from metal parts, medium from glass fibre and low from wooden parts). The disturbance depends on the amplitude of the scattered signal relative to that of the direct one, and the disturbance is typically increasing with the frequency of the signal. In the case of TV signal interference, it is typically below a modulation threshold of about 2 dB at distances less than 10 rotor diameters from the turbine. The cost of providing cables instead of aerial antennas to any building located within this radius is normally negligible and routinely considered part of the windmill installation cost. For frequencies used by navigational and military intelligence systems, the interference is found to be less than that of a static building of the same height as the wind turbine (44).

Impacts on ecosystems would be mainly from extraction of materials used in the construction. An operating wind turbine is a smaller hazard for birds and flying insects than a similar static structure (51). A few bird kills have been observed in cases of turbines located along major migration paths of songbirds, while larger birds usually migrate at heights above 500m. The slowly turning blades of modern windmills allow birds to take evasive action, as several studies have shown that they do in practice. The hazard is thus greatest in misty weather with winds below the minimum for the turbines (44).

Microclimatic impacts are resulting from the slowing down of the wind, necessarily associated with wind energy extraction. This can lead to altered evapotranspiration patterns, and may have positive impacts on soil erosion. The slowing down of the wind is felt over an area roughly twice the swept one and has disappeared ten rotor diameters downwind (60), or sooner, depending on the stability of the natural wind direction. Influence on rainfall and carbon dioxide concentrations at ground level are limited to the immediate area below the turbine (44).

In order to compare the different impacts described above, and in order to compare different energy technologies with different types of impacts, it would be convenient to have a common unit, say monetary value, into which all impacts might be translated. Systematic approaches to this monetizing approach have proven difficult. Certain damages have identifiable costs, but others (e.g. visual impacts) not. Methodologies used in such cases have included "avoidance cost", i.e. finding the cheapest technology that does not have the impact in question. This is unsatisfying, because the replacement technology will always have other impacts that differ from those of the technology being replaced. An alternative is contingency valuation, e.g. performing interview studies inquiring what amount of money people would be willing to pay to avoid a certain damage. Clearly this is a shaky procedure that will be influenced by day to day information flows and competing priorities. Also hedonic costing, based on preferences revealed through e.g. property costs close to and far from a given energy facility, or the value of life defined as the amount of life insurance people take out, are evidently loaded with problems and uncertainties. Some studies further propose to distinguish between internalized and external costs, e.g. claiming that one can identify, what impact is taxed by a given energy tax (58; and other studies in the US/EU externality projects).

The technique of life-cycle analysis may be defined in such a way, that identifying a common unit is not essential (61). The person or persons that have to assess and make decisions based on life-cycle analysis of alternative solutions to a given problem may be presented with sets of impact profiles, where each item has a different unit, but the same unit is used for all alternative technologies. In those cases where monetizing is possible without introducing new levels of uncertainty it may be done, but the technique of impact profiles ensures that monetized and otherwise quantified impacts are presented in the same way, and even that non-quantifiable impacts can be presented on the same footing, as long as the qualitative impacts of different technology solutions can be distinguished. Figure 13 gives an example of such impact profiles for wind-based and coal-based electricity production (47,62). It is assumed that no specific energy storage facilities are required in the wind case, corresponding to a penetration of under 30% in a large, internationally connected utility system (63).

SYSTEMS INTEGRATION ISSUES

Issues of integration occur both on the level of wind energy systems and in integrating wind with other power systems. As regards systems of wind energy converters, the advantage of having wind turbines scattered in a decentralized fashion is rather evident, as the wind regime will change over length and time scales in unison, according to what is termed the ergodic hypothesis (34). This means that differences in power production over time may to some extent be compensated by having wind turbines at different locations feed into a common grid. Small spatial separation will take care of short-term fluctuations, whereas continental dispersal is needed to average out synoptic differences (i.e. the effects of passing front systems). This type of integration may reduce the need for energy storage in case of a large penetration of wind power in the electricity system, just as a short-term storage equal to 10-20 hours of demand makes the loss of load probability (LOLP) of a single wind turbine similar to that of a nuclear power plant (64). To reduce the LOLP to the same value as ordinary fossil power plants, about 1000 hours (a little over a month) of storage is needed (Figure 14) (65), Alternatively the integration of turbines over a distance of 240km will increase the availability of half the average power output from 50 to 70% of time (65). In order to average out synoptic differences, clearly a larger area is needed. This does not mean that storage will not be useful in a pure wind energy system, because with storage the minimum production needs not match demand, and thus the installed capacity can be reduced.

Ease of construction and maintenance conditions similar to those of conventional power stations have led to the clustering of windmills into wind farms, in particular those owned by power utilities. This is equally true for the recently added off-shore wind farms (Figure 8d), being erected in regions with high population density and many competing uses of the most windy sites on land. This raises the question of interference between wind flows in wind farms, and consequently creates an optimization issue between density of wind turbines and power loss due to reduced winds. Calculations of wake effects indicate that the power losses behave approximately as indicated in Figure 15. In order to avoid significant power losses in a large wind farm, a spacing of 20 rotor diameters is needed (34,66,67). This would be somewhat reduced in regions with incoming winds from shifting directions, and in bi-directional flow regions such as valleys or passes, the turbine separation perpendicular to the wind direction can be just a few rotor diameters. Current wind farms often accept a fairly significant energy loss.

Electricity systems involving a combination of wind turbines with other forms of generating equipment poses interesting layout and control questions. Which energy systems integrate easily with wind, and in case they can be regulated then how is this best done? Considering first combinations of wind with other renewable energy systems, there is advantages in diurnal and annual variation combinations of wind with solar (photovoltaic) and with hydro power, at least in some regions of the world (68). As regards hydro with annual reservoirs, found e.g. in Norway, there is no penalty in using this as a backup for even a quite large wind system, because as mentioned above, periods with low wind power production will last at the most around a month, and therefore the "borrowing" of hydro power with subsequent paying back of wind power will only slightly influence the water level in the seasonal hydro reservoirs.

Combinations of wind power with biomass used in power plants (either directly by combustion or indirectly after biogas production) will behave like fossil fuel combinations, as biomass can be stored in much the same way as e.g. coal. The regulation of such a combined system can follow various types of control strategy. Either one may have a sufficient amount of quick-start gas turbines in the system to take care of sudden changes in wind production, or one may have a number of coal- or gasfired power plants as spinning reserves, in order to avoid to have to wait for the warming period associated with conventional plants (although this is getting shorter with modern injection technology). The control may be based on wind power forecasts taken from general meteorological forecasts, or just on extrapolations of previous levels of wind production. Simulations have shown, that the latter strategy is probably good enough for all practical purposes (63).

ECONOMIC ISSUES AND TRENDS

The very uneven penetration of wind turbines in countries with similar wind resources is the result of widely different support in terms of utility interfacing, compensation for externalities and financing schemes. With respect to grid connection, there is first the installation cost. In some cases, the distribution line being hooked into is too weak and must be reinforced. This may have been needed anyway due to increased customer load, so how do the power company and the wind turbine owners share the cost? Then there is the buy-back of surplus wind power. Is the utility required to buy back such power, and at what price? Is it just the avoided fuel cost, or is wind given some capacity credit and premium for being much less polluting than the average power plant? If the utility does not consider externalities, then maybe society does and gives tax credits to less polluting energy systems? Finally in some countries, utilities have concessions allowing them to accumulate capital for future investments, whereas in other countries they have to finance new investments by loans. The windmill people are mostly confined to private loans, and sometimes on terms less attractive than those offered a large utility.

USA was the first country to establish fixed power buy-back rates (through the PURPA act), but there are still countries, where it is not allowed for independent producers to hook up to the grid and sell power. Table 6 shows buy-back rates in some European countries, along with information on whether investment subsidies are given. Denmark is the only country having a fixed procedure for calculating grid-connection costs, with the principle that the windmill owners pays the connection installation and the power company any grid enforcement made necessary by the turbine. The conditions gave changed in the countries listed. Denmark e.g. had a 30% capital subsidy to start the wind business during the late 70ies, following a suggestion by the wind lobby (69).

Figure 6. Wind power buy-back rates and investment subsidies (a)

Country	Small consumer's electricity price (ecu/kWh) (d)	Wind power buy-back rate (ecu/kWh)	Investment subsidy
Denmark	0.112	0.083	none
The Netherlands	0.084	0.035-0.069	up to 35%

Germany (b)	0.133	0.118 (0.086)	(up to 60% or 46 kecu)
United Kingdom	0.109	0.136 (0.092)(c)	none
Italy	0.113	0.087	20-40%
Spain	0.13	0.077	none
Sweden	0.078	0.034	25%

(a) Collected by EJ van Zuylen, AJM van Wijk, C Mitchell. 1993. Comparison of the financing arrangements and tariff structures for wind energy in European Community countries. Utrecht: Ecofys consult

(b) The high buy-back price is available only to those not receiving an extra investment subsidy

(c) The lower price applies after 1998

(d) 1 ecu is about 1.25 US$

In Denmark there are very strict rules for the shareholders of a wind turbine, aiming to prevent use of wind power as a tax evasion scheme. Each shareholder must live close to the installation and cannot hold shares corresponding to more than 150% of his own electricity consumption. If the shareholders use a particular company form called IS, there is no taxation of profits up to 10%. Wind power is also relieved of energy and carbon taxes. There are discussions underway to relax the condition of nearness, in order that people living in big cities can also support wind energy.

In the Netherlands, most wind turbines are owned by power companies. They can use the carbon taxes paid by the consumers for wind energy investments. In Germany and the UK, project financing is common, and in Germany 50% can be financed by low interest loans through the subsidized "Ausgleichbank" (DAB).

Due to the ambitious plans for wind energy expansion in several European countries, the question of capacity credit is likely to come up, together with issues of energy storage or schemes for operating the system in ways that avoid the need for storage. The discussion in the previous chapters shows, that intelligent dispatch (that may involve collaboration between several countries) and relatively short-term storage facilities will make it possible for wind energy to deliver any share of the demand, and that the resources to do so are available, but that in some cases the extra expense of off-shore siting may be needed in order to avoid land use conflicts. In countries which already have a considerable share of wind power, the substitution of large turbines for the smaller ones presently occupying the best wind sites is a policy which will minimize environmental intrusion. In Denmark, the present 3% of electricity from wind could in this way rise to nearly 100% with the same number of turbines (about 4000) as today (70).

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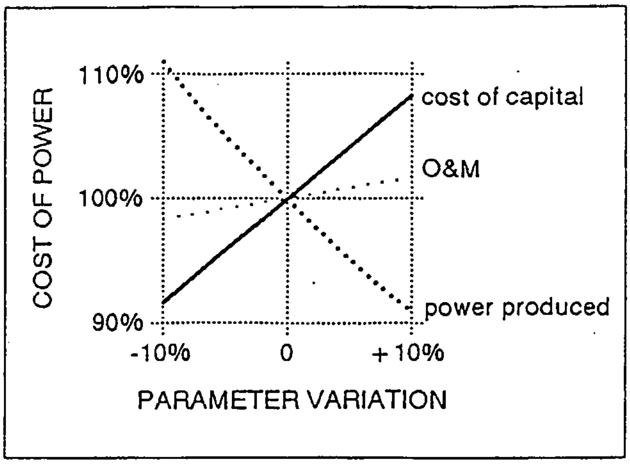

Figure 1. Sensitivity analysis indicating the dependence of the cost of wind power on the most uncertain parameters.

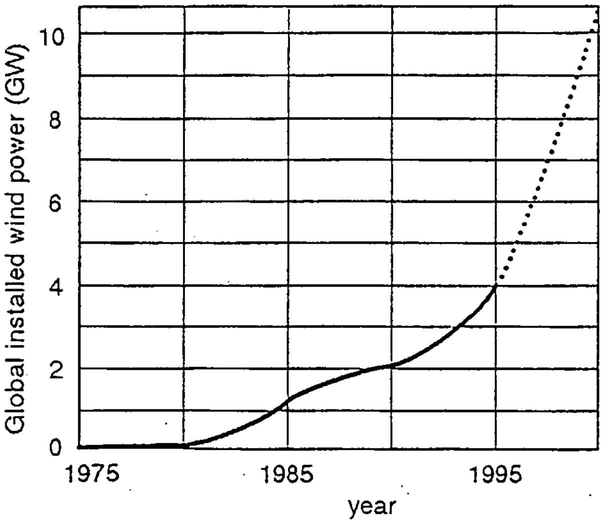

Figure 2. Worldwide penetration of wind power (GW installed) and government planned expansion to year 2000 (with use of (1)).

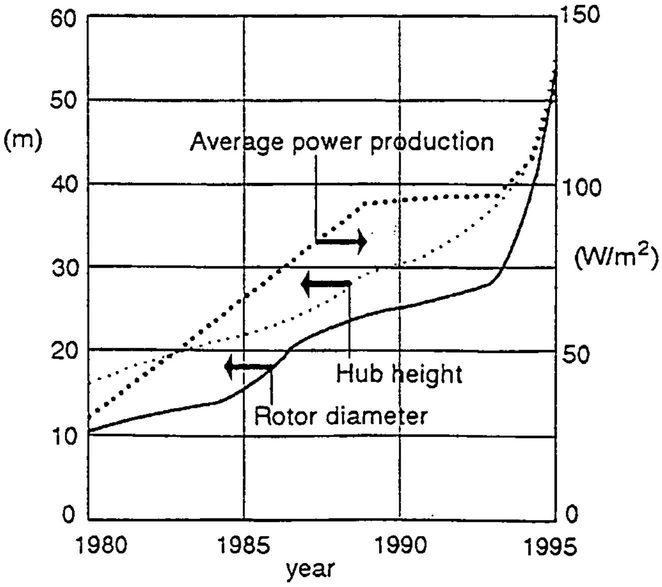

Figure 3. Development in average unit size and specific power output for turbines installed in Denmark (Based on (2), Windmill Price List, Danish Technological Institute, October 1994, and JOULE II Project Synopses, Brussels: European Commission 1994).

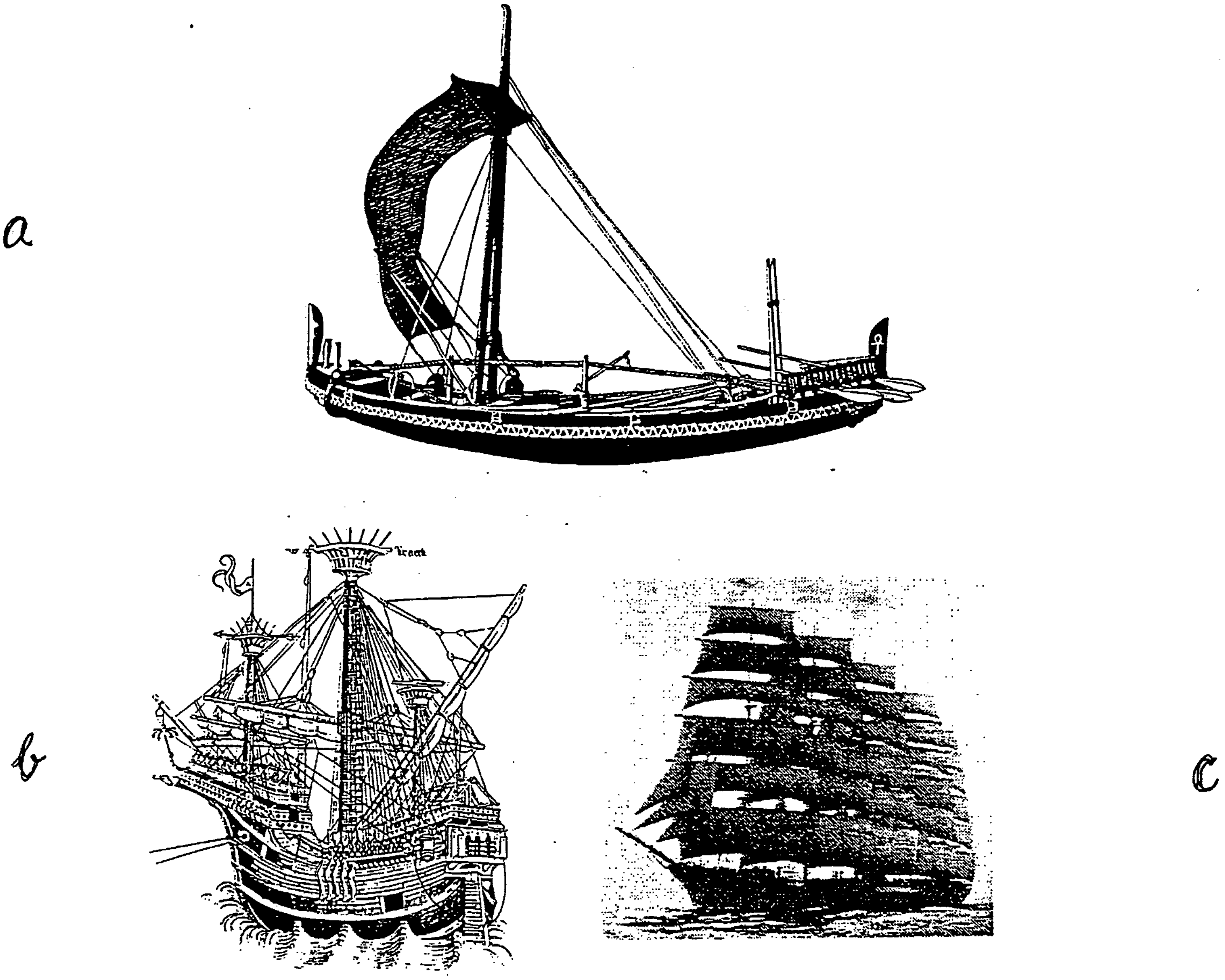

Figure 4. Windpowered ships. (a) Egyptian ship c 2500 BC (3); (b) Flemish merchant ship c. 1480 (4); (c) German ship "Preussen" c. 1880 (Peabody Museum, Salem).

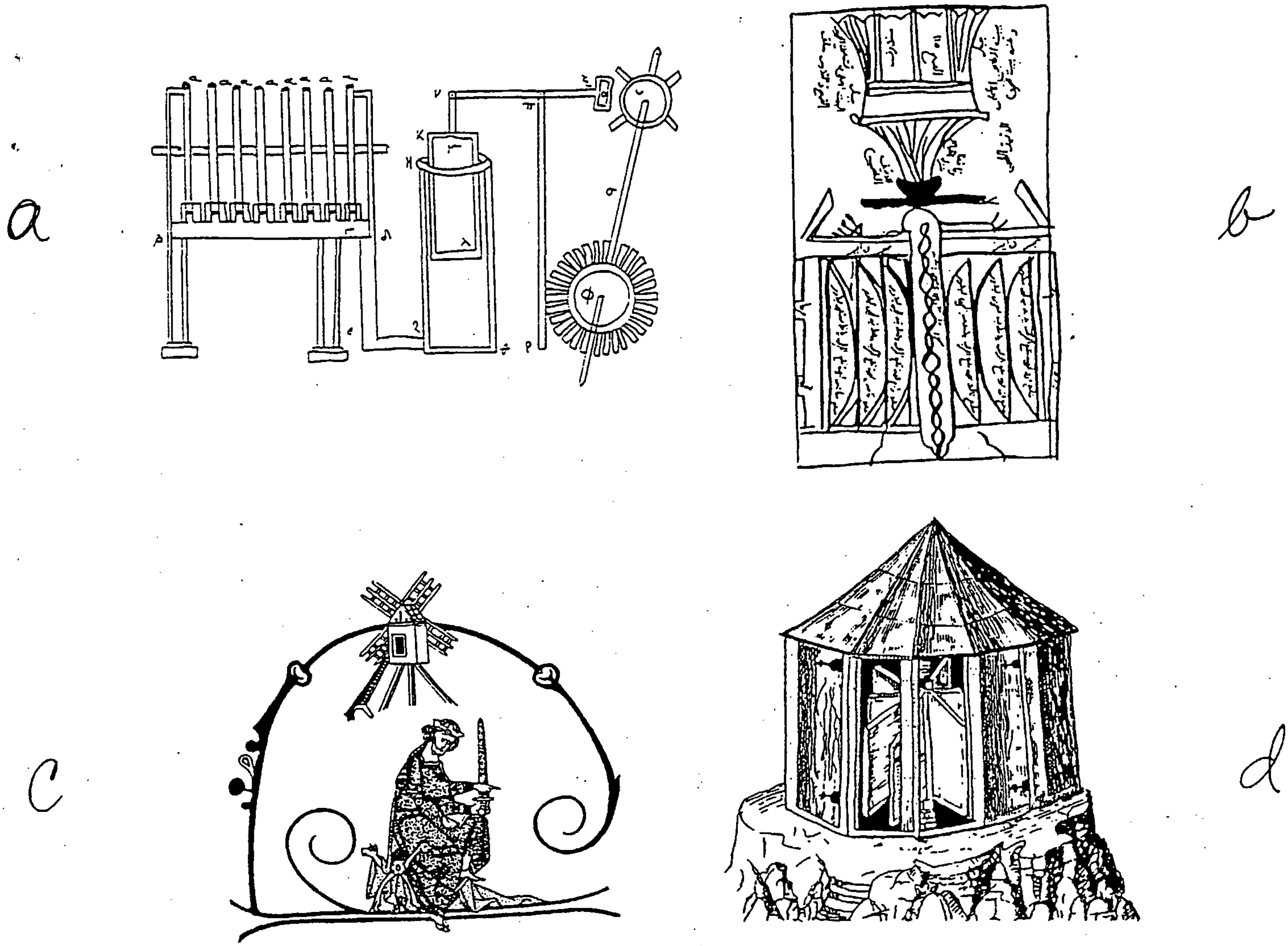

Figure 5. Early windmills. (a) Heron's windpowered organ, drawing from 516 (7,10); (b) earliest drawing of Persian windmill, c. 1300 (16); (c) earliest drawing of European post-mill, 1270 (Canterbury psalter, see 18); (d) Vertical axis mill on Crete (Grünemberg, 1486, see 10).

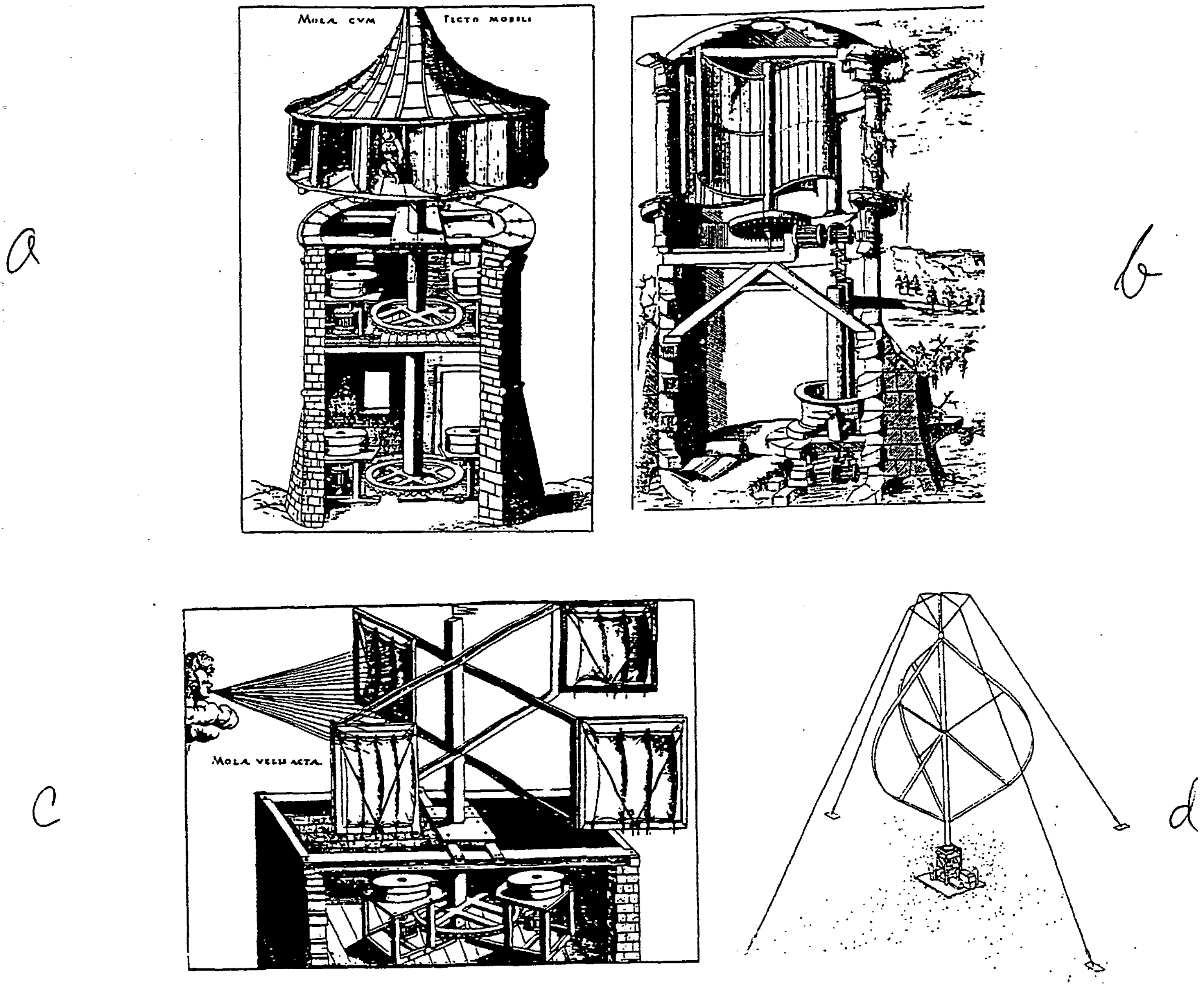

Figure 6. Vertical axis turbines. (a) from Veranzio 1595 (see 18); (b) from Besson J. 1578. Theatre des instruments. Vincent Lyons; (c) also from Veranzio 1595; (d) Darrieus turbine 1990 (24).

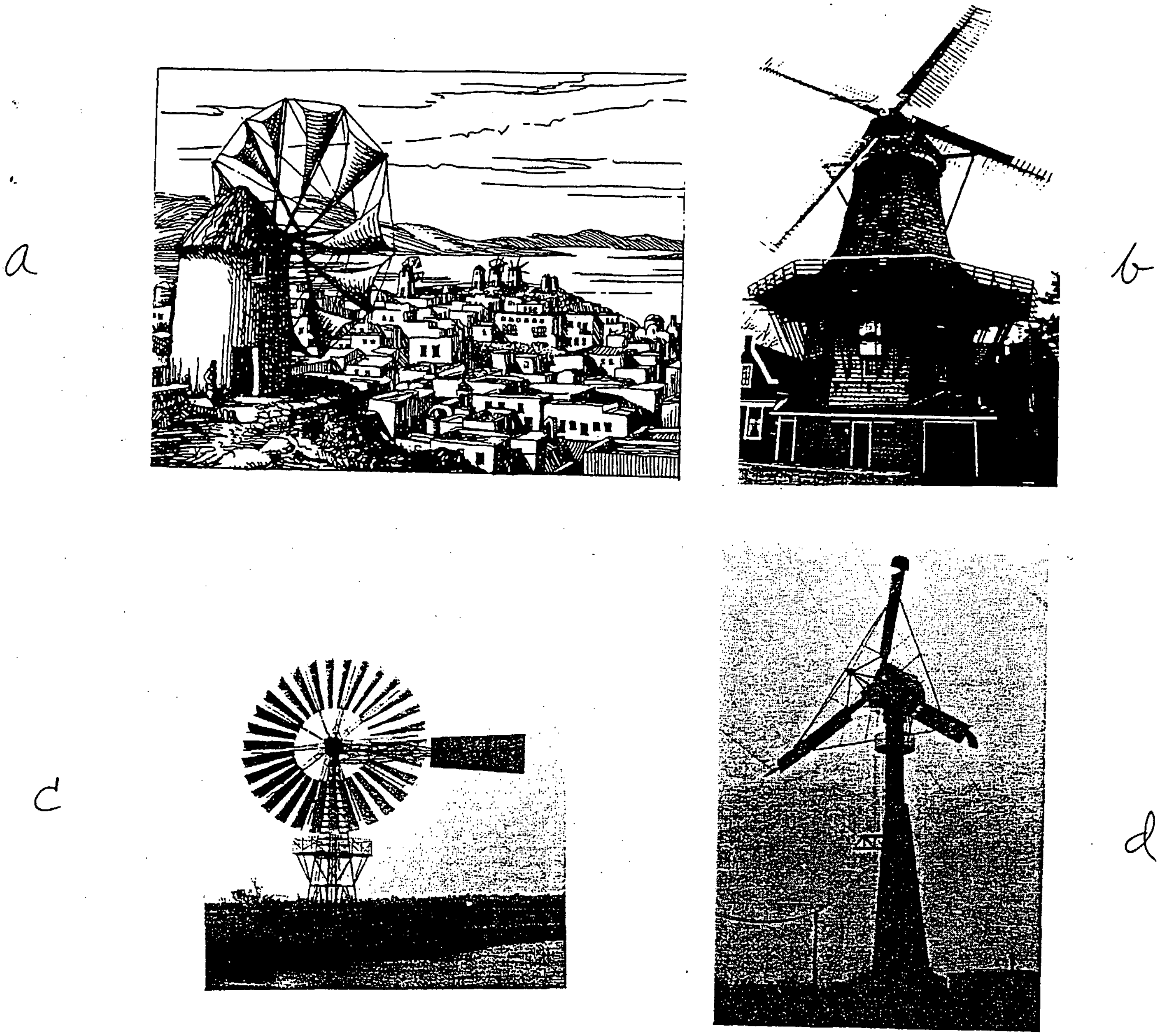

Figure 7. Horizontal axis turbines. (a) Mediterannean sailtype; (b) Dutch top-yawing mill from 1658 (26); (c) American multiblade farmmill c. 1920 (26); (d) Danish AC producing turbine at Gedser 1959.

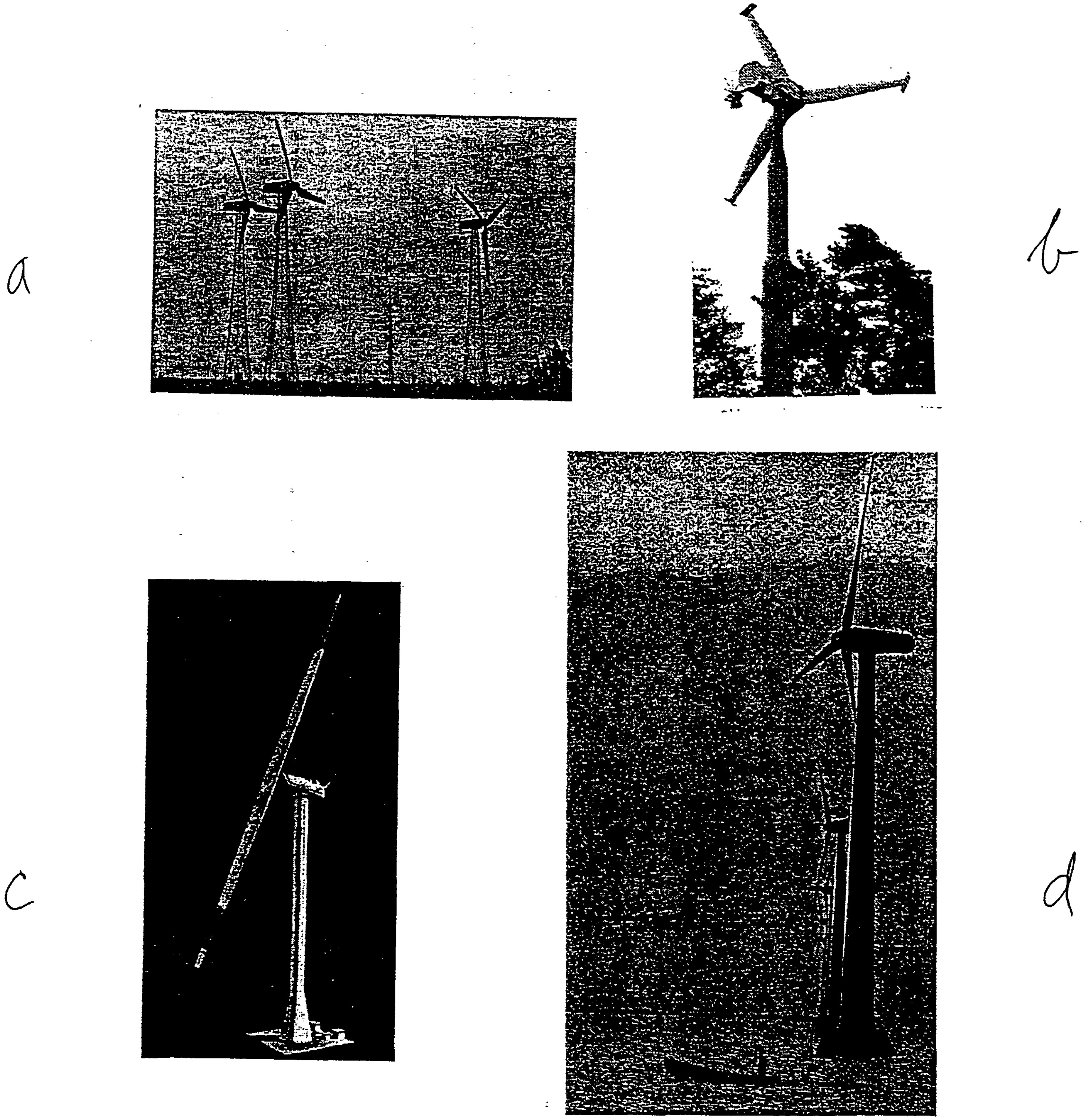

Figure 8. Modern windmills. (a) Danish turbines 1979; (b) Dutch tipvane construction (26); (c) US Mod-2 1982 (41); (d) Danish off-shore windpark at Vindeby 1993 (Bonus turbines).

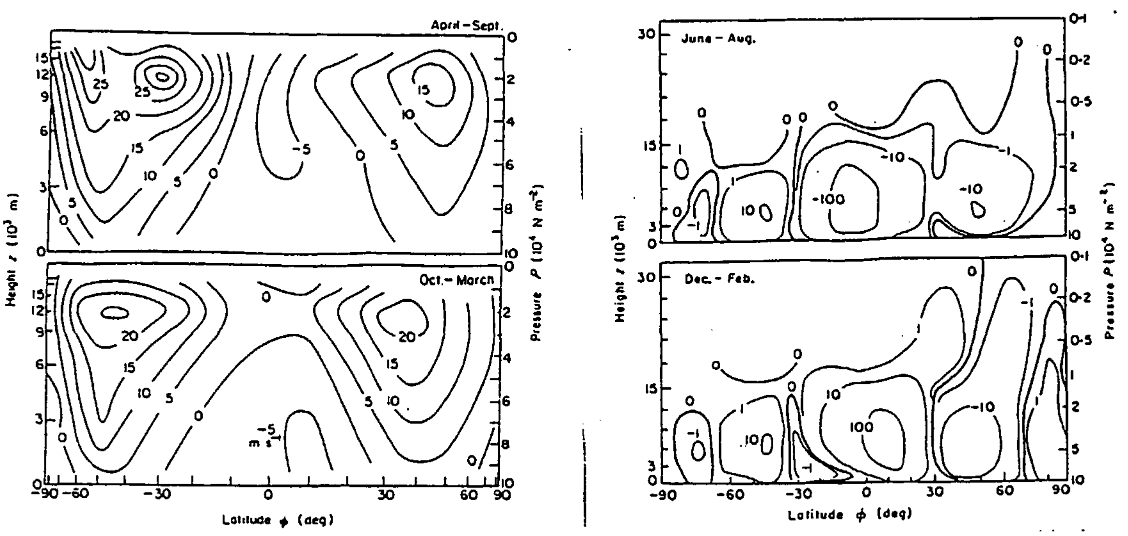

Figure 9. Summer and winter longitudinal winds (a) and streamlines of latitudinal wind patterns (b; mass transport in 10^9 kg/s, a positive value means Northward motion aloft)(34).

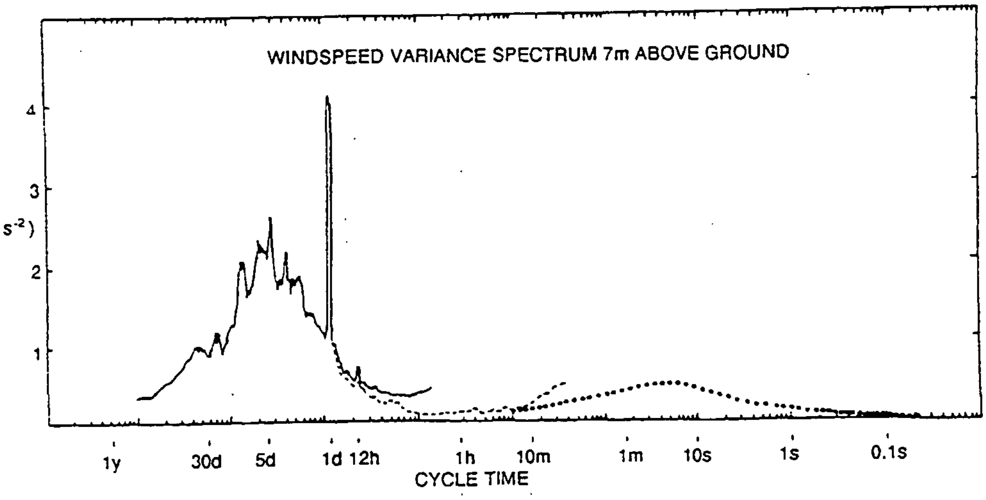

Figure 10. Frequency spectrum of winds near the ground, showing synoptic periods (5d), solar radiation effects (1d) and turbulent motion (10s). Based on EL Petersen, 1975. <u>On the kinetic energy spectrum of atmospheric motions in the planetary boundary layer</u>, Risø Nat. Lab. report 285; and (34).

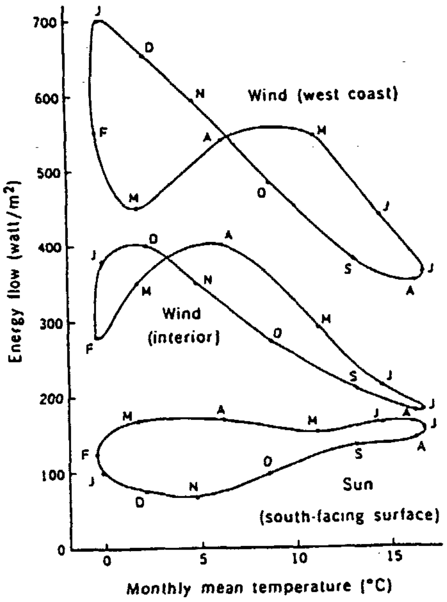

Figure 11. Comparison of seasonal variation in wind (inland and coastal sites) and solar radiation, in Denmark (38).

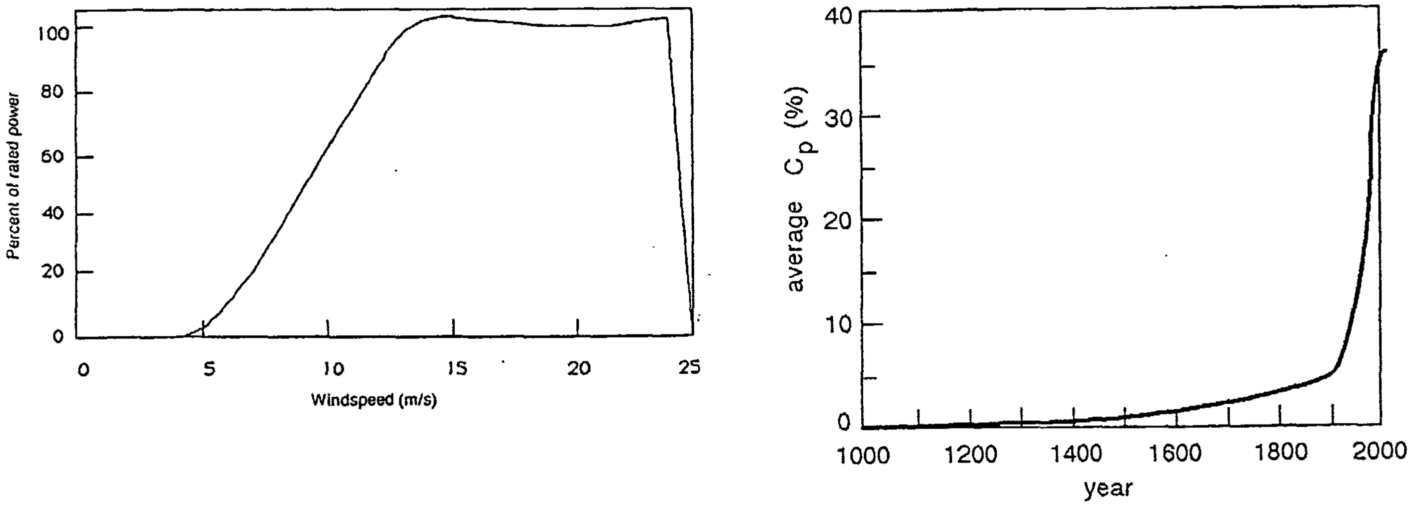

Figure 12. (a) Typical power output from modern glass-fiber rotor blades. B Sørensen, The Status of wind generators in Europe. Sydney: Energy Authority of NSW report 86/18; (b) Average power coefficient C_p (power produced by the turbine, over power of the undisturbed wind passing through an area equal to that swept by the rotor) for typical windmills through time.

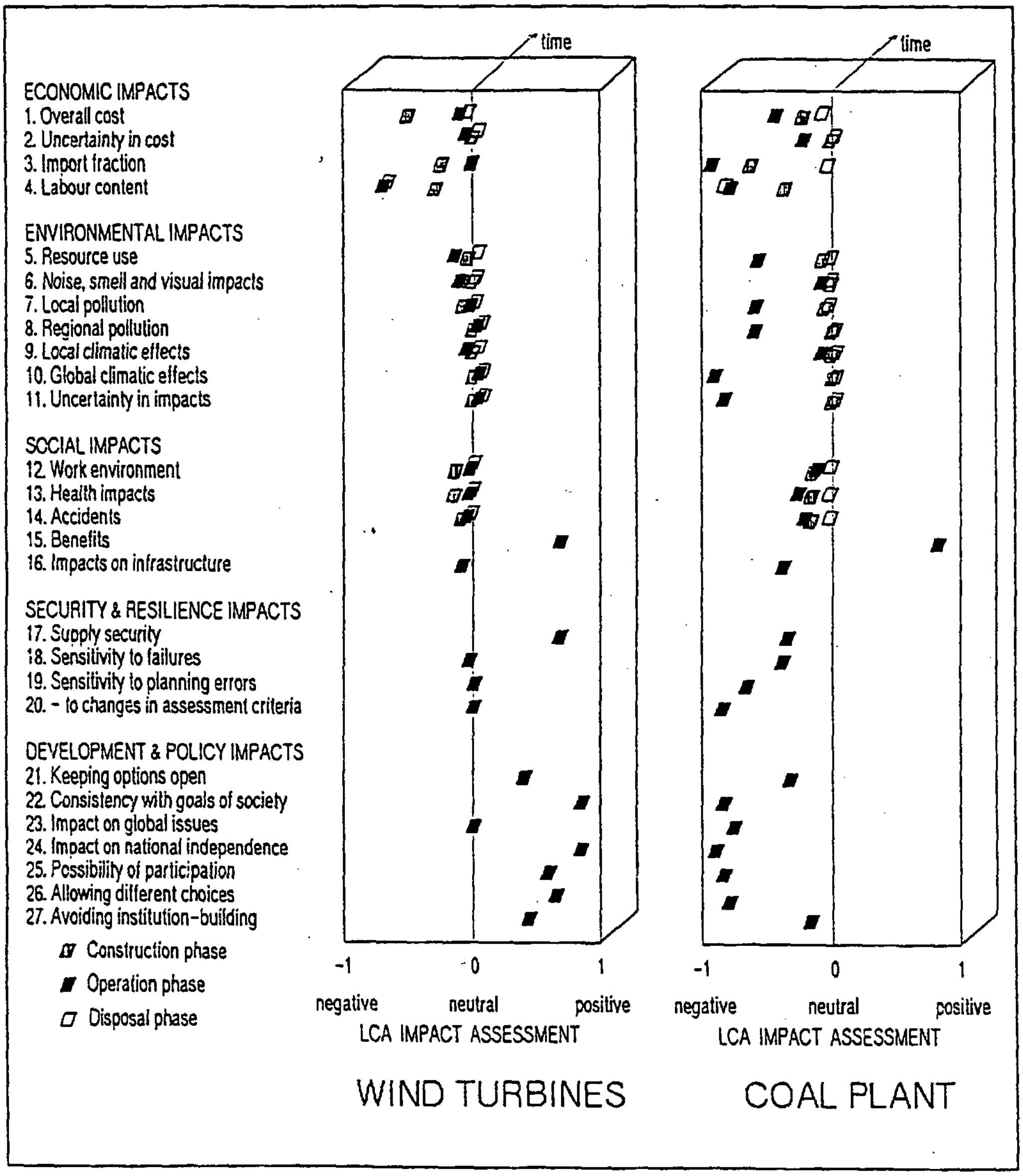

Figure 13. Summary of life-cycle impacts for wind and coal power plants. Some of the impacts are quantified (see text), others not (62).

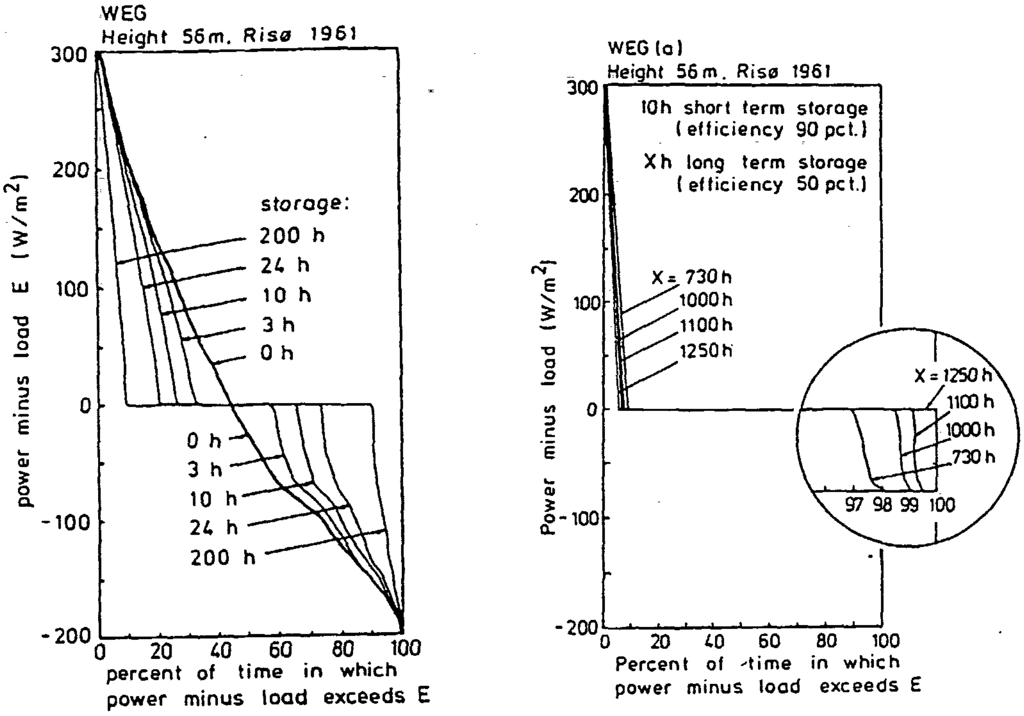

Figure 14. Model investigations of the effect of storage ((a) short-term, (b) long-term) on the power duration curve of a typical windmill (65).

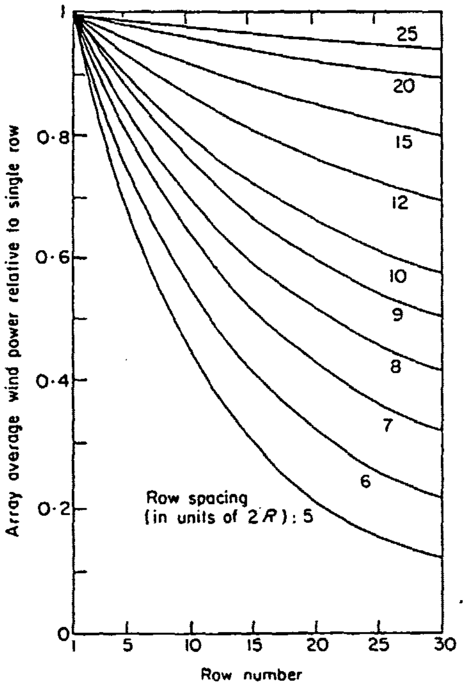

Figure 15. Model calculation of the reduction in wind power through a large windfarm with a regular turbine spacing. Based on (66; 34).

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