WIND ENERGY

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Summary

Wind resources and conversion technologies are reviewed, including an assessment of direct, social and environmental costs. The potential for greenhouse emission reduction is discussed.

1. Worldwide Distribution of Wind Energy Resources

Winds are caused by differential heating of the atmosphere, in combination with Earth's rotation and friction within the atmosphere, and between the atmosphere and the surface of the Earth. Lorenz (1967) has estimated that about 1200 TW on average are used to sustain the general circulation, which is under one percent of incoming solar radiation, cf. Figure 1.

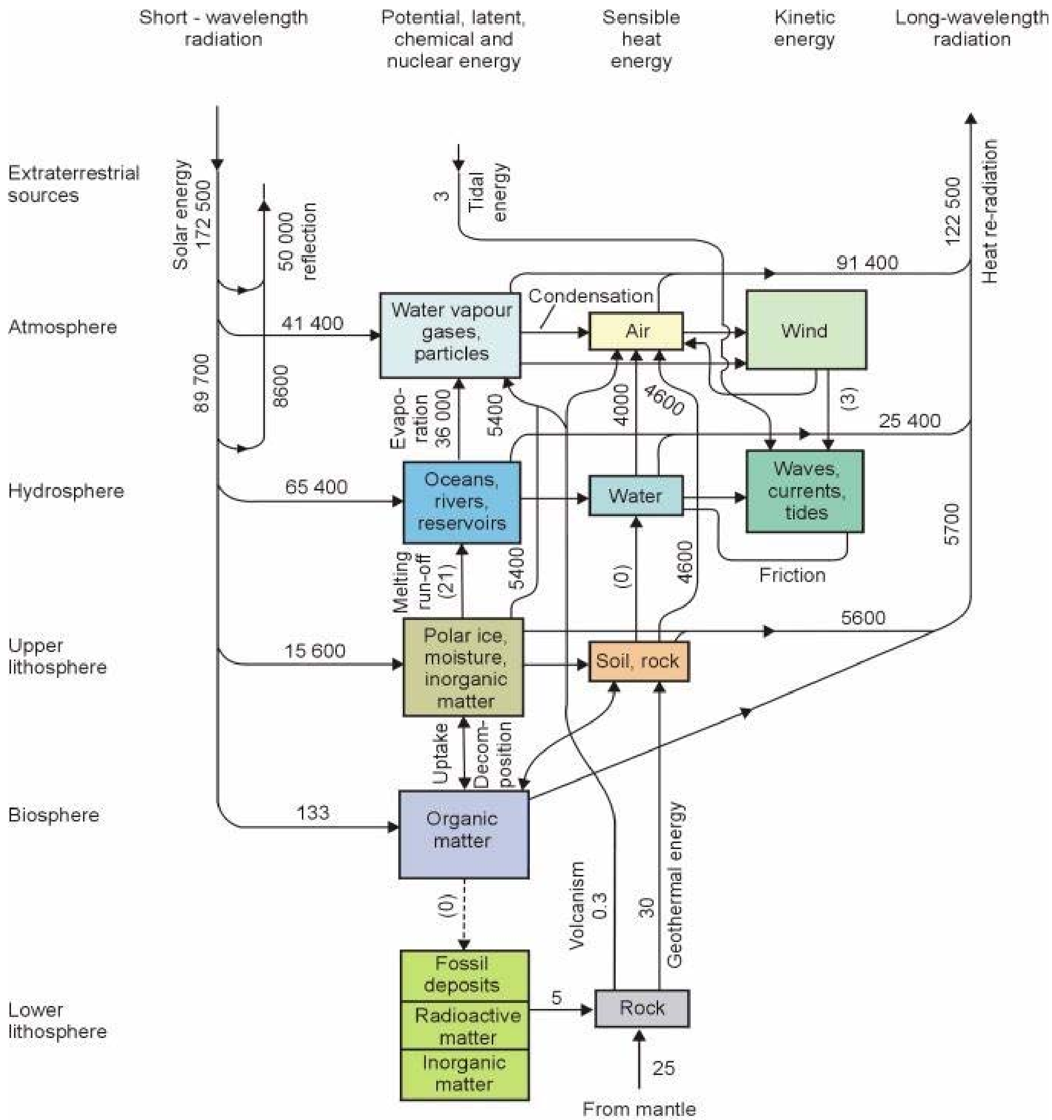

Figure 1. Energy cycle in the Earth-atmosphere system without anthropogenic interference (unit TW) (Sørensen 1979).

The kinetic energy in the circulation is 750 EJ, so the turnover time is around 8 days (Newell et al. 1969; Sørensen 1979). About half the energy is dissipated in the upper atmosphere, the rest near the surface. As only 3 TW are estimated as being used to create waves (Gregg 1973), land surface are responsible for most of the fiction. 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 that create roughness in the surface. One may then ask, what would be the effect of extracting power corresponding to a large part of the energy influx that maintains the circulation? These mechanisms have been discussed in Sørensen (1996): decreased evapotranspiration and increased friction near the ground, causing the apparent low-altitude wind speeds to become lower, although the gradient upwards might be stronger, because the stratospheric jet streams are unlikely to change. The appraisal concludes that even if the entire world electricity use were covered by wind, this would, at present, only constitute approximately 1 TW, which would be very unlikely to have any effect on global circulation. In other words, the general resource availability is huge, and real question is, how much of this resource mankind can harvest in a convenient way, and of course, how the resources are geographically distributed, as compared to the power demand.

1.1. Physical Potential, Wind Maps

The physical potential for wind energy extraction varies considerably between regions and even nearby locations. This is due to climatic circulation particulars as well as local differences in surface roughness. The energy flux associated with the wind is proportional to the third power of the wind speeds, which helps to expand the differences between sites.

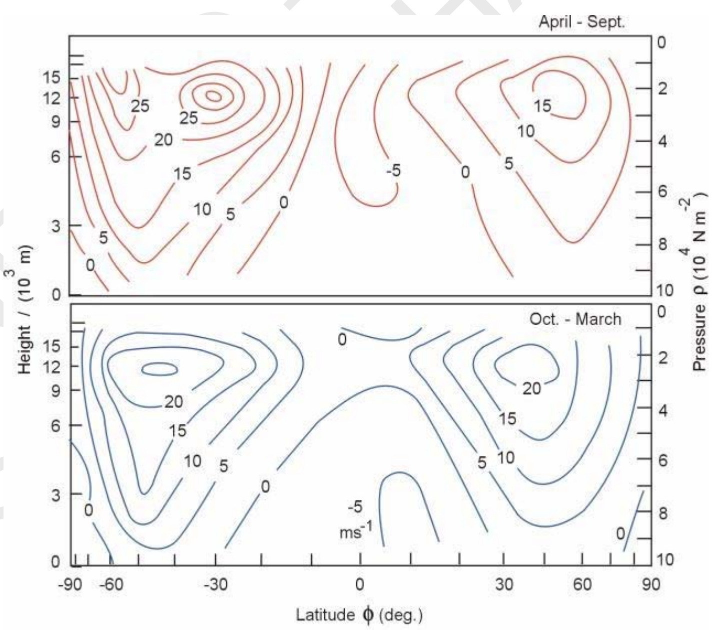

Figure 2. Summer and winter longitudinal winds (Sørensen 1979).

The winds at a particular location on the Earth's surface are determined by the geostrophic wind aloft, and the roughness of the terrain (Sørensen 1979). The geostrophic winds follow regular patterns determined by the mid-latitude jet-streams and the Equatorial trade winds (see Figures 2 and 3), but overlay the patterns of short-term weather systems. The roughness is generally high for uneven topography, including built-up environments, and low for flat plains and open sea (Sørensen 1979).

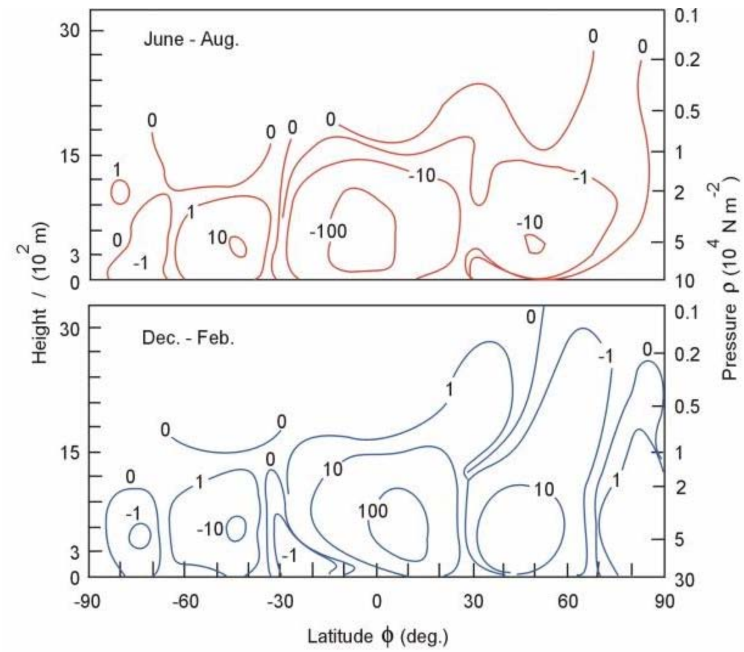

Figure 3. Streamlines of latitudinal wind patterns (mass transport in 10^9 kg s^{-1}, a positive value means Northward motion aloft) (Sørensen 1979).

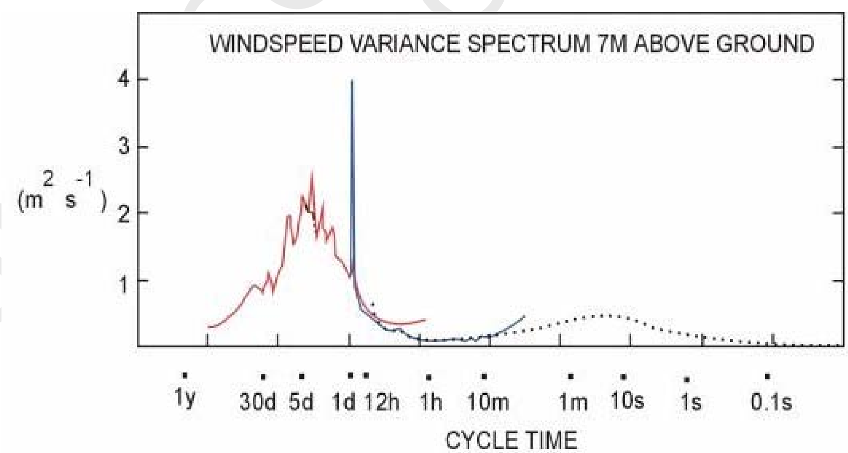

Figure 4. Frequency spectrum of winds near the ground, showing synoptic periods (5 d), solar radiation effects (1 d) and turbulent motion (10 s) (Petersen 1975; Sørensen 1979).

The 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 (Sørensen 1979). The variations in wind speed depend on passing weather front systems, on the heating by sunlight, and for a short time scale, on stability (gustiness). Figure 4 exhibits clear peaks in the variance spectrum corresponding to the mentioned periods. Seasonal variations of the power of the wind vary with location, and in several countries (e.g. in Northern Europe) there is a variation that is anticorrelated with that of solar radiation (Sørensen 1975).

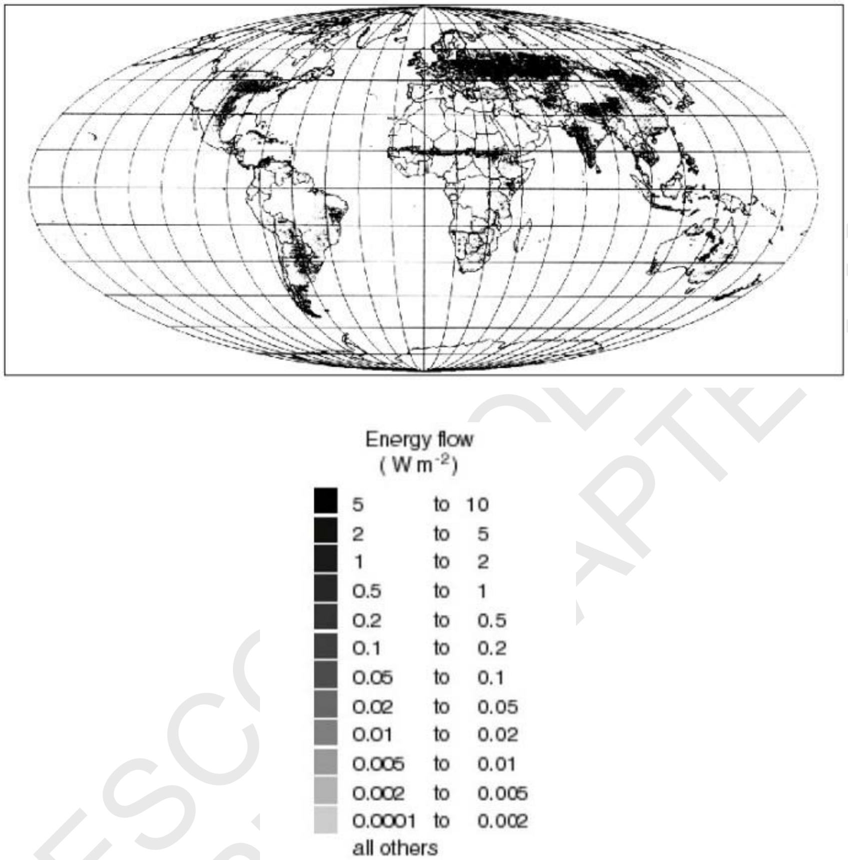

Figure 5. Potential annual average production from decentralised wind turbine power plants near farms, i.e. on crop and range-land, with transmission and storage cycle losses subtracted (scale given in Figure 5a).

Based on cartological information on topography and measured geostrophic winds, wind maps have been constructed, e.g. for Europe and the USA (Ellis et al. 1986; Troen and Peterson 1989). These maps divide the land into areas with average wind speeds in given intervals. The European map differs from the US one by using a classification according to geostrophic winds. In order to obtain the wind speeds near the ground, folding with roughness estimates are necessary. More recent methods for assessing potential wind power production use global circulation models to ensure the consistency of wind data measured at different locations and different heights, and to construct global maps that can be used also in regions without adequate data (due to the general validity of the circulation models). These models also allow wind power production to be estimated at different times and thus give information on variability between seasons and between years. An example of such estimates of potential wind power production is shown in Figures 5 and 6, for wind turbines placed at a height of approximately 70 m on agricultural land and on marginal land, respectively (Sørensen 1999a, b). Environmental constraints and other land uses have been considered, leading to a maximum wind turbine swept area of 0.1 per cent of the land area. Also losses in conversion, storage and transmission to and from storage facilities have been considered in the study underlying Figures 5 and 6.

1.2. Practical Potential for Wind Turbines

The practical wind potential shown in Figures 5 and 6 is smaller than the physical one for a number of reasons. The physical potential generally increases with height, and at a given time, technological capability limits the height at which extraction is practical. Current wind turbines have hub heights of around 50 m, but only a decade ago the average hub height was much smaller.

Other considerations include land use (considered below) and environmental aspects. Generally, these issues may be resolved differently for different societies, and depending on whether a semi-centralized or dispersed siting of wind turbines is preferred. Dispersed turbines can be more easily integrated into the landscape, but of course the total wind energy extraction may be less than the full potential. Centralized "wind parks" will cause more of an impact, and often this results in placing more turbines on a given land area, once it has been accepted for this purpose, than would be dictated by considerations of maximum extraction efficiency. In other words, the turbines are too close to each other and a certain degree of "shadowing" has to be accepted. Figure 7 indicates a calculation of the decrease in power output through a wind farm, as a function of separation between units (several other calculations confirm these reductions, see e.g. (Builtjes and Smit 1978).

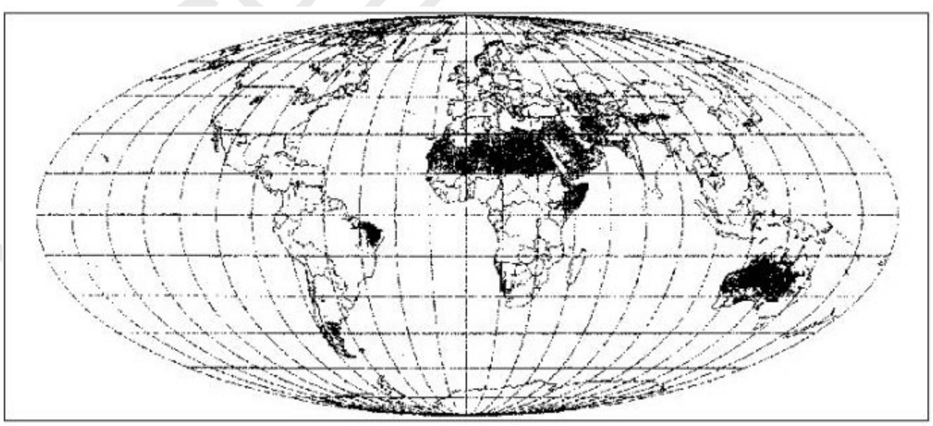

Figure 6. Potential annual average production from centralised wind turbine power plants on marginal land, with transmission and storage cycle losses subtracted (scale given in Figure 5a).

Most modern wind turbines have break-in speeds of about 5 m s^{-1}. This means that any power in the wind deriving from speeds below that limit will not contribute to output.

Turbines sensitive to low-winds usually have a very low level of power extraction at high winds (e.g. the American multiblade windmill type). Also, behavior at high winds plays a role. Some turbines will asymptotically reach a constant power output level, while others give no power if the winds speed is above a certain value. The result is that neither low nor extremely high winds contribute significantly to the average power production, and thus a site drawing a large fraction of its power from any of these two limiting situations will not be attractive for wind turbines of the kinds manufactured today.

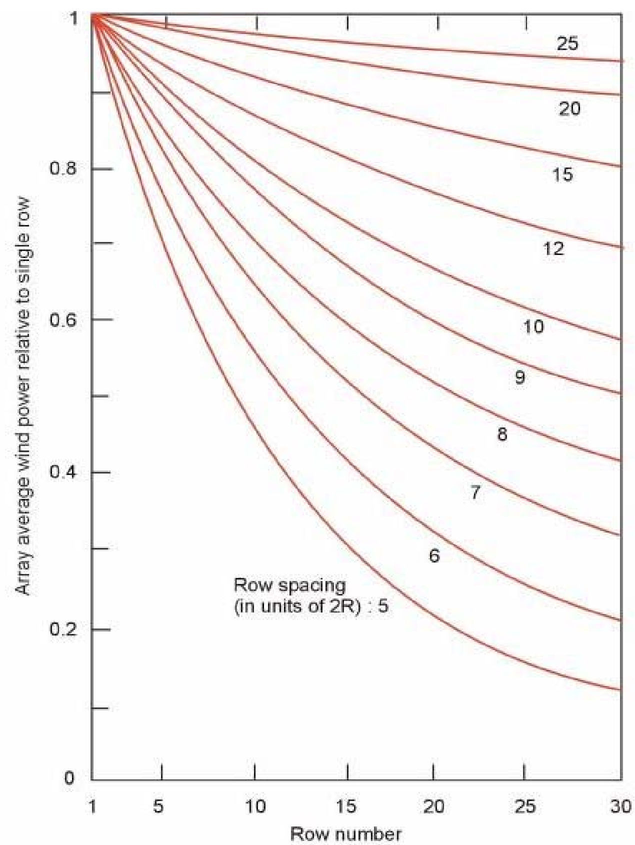

Figure 7. Model calculation of the reduction in wind power through a large windfarm with a regular turbine spacing. Based on Crafoord 1975; Sørensen 1979.

1.3. Restrictions due to Competing Land Use

The area planning in most countries sets aside certain areas for urban development and for recreational purpose, including the preservation of nature parks and landscapes of particular value. Some countries operate with planning zones, that exclude placement of energy equipment on coastal strips, which would conflict with the optimum use of wind power, because coastal strips are often most favoured by the wind.

Again, there is a difference between the placement of individual wind turbines, which can be done near farms or other scattered settlements without seriously affecting land use planning, and setting aside dedicated areas for wind farms. The current tendency is towards always considering a multi-purpose use of land areas, i.e. placing wind turbines alone or in clusters, but in such a way that it is possible to conduct agriculture between the turbines. This is feasible, because the actual area occupied by the turbines is small, and no restrictions on agricultural land use 1 and 2 rotor-diameters away from the turbine have to be imposed. Only access roads needed for maintenance of the turbines will subtract from the available land. Noise emissions (considered below) cause no serious conflict with this type of combined land use.

Estimates of the impact of more or less stringent criteria for exclusion of areas for wind energy utilization has lead to estimates of up to 10 per cent of national land areas as being suitable.

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