WIND AND SOLAR RENEWABLE ENERGY POTENTIAL RESOURCES ESTIMATION

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Contents

Summary

The atmospheric environment is potentially an infinite and sustainable source of energy for human needs. The Sun is not only provided with much more energy than needed to meet the energy demand on Earth, it also controls the energy budget of the Earth and contributes to the generation of the wind systems at global scale. Solar radiation and winds are the fuel for solar and wind energy on Earth. The goal of this chapter is to introduce the basic knowledge on atmospheric physics and dynamics at small and intermediate scale in order to quantify wind and solar potential at some specific location or region. Independently of the technology and its efficiency, the chapter addresses issues such as the availability, variability and predictability of the energetic resource of a given environment. These issues are of high importance regarding the present environmental and socio-economical context. It is characterized by an increasing world population associated with an increase of standard of living, limited fossil fuel based

energy resources and climate change. One of the main challenges for the 21st century is thus most probably to develop renewable energy production with low emission of greenhouse gases.

1. Renewable Wind and Solar Energies: The Context

1.1. An Economical and Environmental Necessity

The current world population of close to 7 billion is projected to reach 10.1 billion in the next ninety years. It should reach 9.3 billion by the middle of the 21st century, according to the medium variant of the *2010 Revision* of *World Population Prospects*, the official United Nations population projections prepared by the Population Division of the Department of Economic and Social Affairs [1]. Much of this increase is projected to come from the high-fertility countries, which comprise 39 countries in Africa, 9 in Asia, 6 in Oceania and 4 in Latin America. Associated with an increase of the world standard of living, the consequence on energy need is dramatic. Indeed, oil production and consumption have increased significantly over the past decades. From 1997 to 2007, annual oil consumption increased by 12% from 3,480 to 3,906 millions of tons (from 72.2 to 81.5 million barrels per day) [2].

To meet this increasing energy demand, the resources might appear limited. Indeed, updated projections of energy demand, production, trade and investment, fuel by fuel and region by region to 2035 provided in the 2010 edition of the *World Energy Outlook* (WEO) by the International Energy Agency [3] confirm the conclusion of its 1998 annual report that the oil peak has been reached around 2010. The oil peak is when the maximum rate of global petroleum extraction is reached, after which the rate of production declines due to the exhaustion of exploitable oil reserves.

In addition to the socio-economical necessity, climate concerns also drive an increasing demand for alternative solutions to fossil fuel based energy sources. Indeed, it was estimated by the US Energy Information Administration (EIA) that in 2007 primary sources of energy consisted of petroleum 36.0%, coal 27.4%, natural gas 23.0%. They amount to an 86.4% share for fossil fuels in primary energy consumption in the world [4] with a world energy consumption growing about 2.3% per year. Comparatively, non-fossil sources in 2006 included hydroelectric 6.3%, nuclear 8.5%, and others (geothermal, solar, tide, wind, wood, waste) amounting to 0.9% [5]. With the crucial necessity to decrease emissions of greenhouse gas, and especially carbon dioxide in the atmosphere, many countries have passed legislation to increase the use of renewable energy sources.

In the US, the energy policy is determined by federal, state and local public entities which address issues of energy production, distribution, and consumption. No comprehensive long-term energy policy has been proposed. State-specific energy-efficiency incentive programs also play a significant role in the overall energy policy of the US. The US had resisted endorsing the Kyoto Protocol, preferring to let the market drive CO_2 reductions to mitigate global warming, which will require CO_2 emission taxation. The administration of Barack Obama has proposed an aggressive energy policy reform, including the need for a reduction of CO_2 emissions, with a cap and trade program, which could help encourage cleaner, renewable, sustainable energy development.

In Europe, the Commission published a White Paper in 1997 setting out a Community strategy for achieving a 12% share of renewables in the EU's energy mix. The decision was motivated by concerns about security of supply and environmental protection. The 12% target was adopted in a 2001 directive on the promotion of electricity from renewable energy sources. The legislation was an important part of the EU's measures to deliver on commitments made under the Kyoto Protocol. In January 2007, the Commission published a Renewable Energy Roadmap outlining a long-term strategy. It called for a mandatory target of:

- A 20% reduction of greenhouse gas emissions
- A 20% reduction of energy consumption
- A 20% share of renewable energies in the EU's energy mix by 2020. The 'Europe 2020' strategy, presented by the Commission in March 2010, incorporated the 2020 climate goals in its flagship initiative to promote a resource-efficient Europe.

In this context, the atmospheric, oceanic and terrestrial environment could be an infinite source of renewable energy for human activity. However, this energy resource is highly “diluted”. Nevertheless, some natural processes or specific geographical configurations may concentrate this energy and optimize the energy conversion. In this article, special focus is put on the atmospheric source of renewable energy, namely wind and solar energy.

1.2. Energy Definitions and Units

Energy is the capacity of a physical system to perform work and exists in several forms such as heat, mechanical energy, electrical energy, or other forms. In the international system, the unit of energy is the Joule. It is named after English physicist James Prescott Joule (1818–1889). http : / / en. wikipedia . org / wiki / Joule - cite_note-01 J is the energy needed to lift an apple of 100g by one meter. 1 MJ (1 million joules, i.e. 1 megajoule) is the heat needed to boil 3 l of water. Power is the rate at which work is performed or energy is converted. The dimension of power is energy divided by time. The unit of power is the watt (W), which is equal to one joule per second. It is named after the Scottish engineer James Watt (1736–1819).http: / / en . wikipedia . org / wiki / Power_ % 28physics % 29 – cite _ note-0

In the context of massive production or consumption of energy, Joule is a quite small unit. The unit to quantify individual energy consumption is for instance the kilowatt-hour (kWh). It is a unit of energy equal to 1000 watt hours or 3.6 MJ. It expresses the heat released by a 1000W heater during one hour. 10 kWh is the heat released by the combustion of one litre of fuel. 47,000 kWh is the French energy consumption per inhabitant and per year. At national or worldwide scale, these are still small units. The tonne of oil equivalent (toe) is often used and expresses the amount of energy released by burning one tonne of crude oil (« mean » crude oil…). 1 toe is equal to 42 GJ (1 billion joules, i.e. 1 gigajoule), or equivalently to 11,600 kWh. 11,400 Mtoe is the World primary energy consumption in 2008.

James Prescott Joule studied the nature of heat, and discovered its relationship to mechanical work [6]. This led to the theory of conservation of energy, which led to the development of the first law of thermodynamics. It can be formulated as “There is no loss or production of energy, just some conversions”.

The form of energy used depends on the capacity of conversion, transport, storage. Primary energy is the energy found in nature that has not been subjected to any conversion or transformation process. It is the energy contained in raw fuels as well as other forms of energy received as input to a system. Final energy is a form of energy available to the user following the conversion from primary energy.

Final forms of energy include gasoline or diesel oil, purified coal, purified natural gas, electricity, mechanical energy, etc… When going from primary energy to final energy, we must take into account the efficiency of the conversion device and of transportation. Useful energy is the portion of final energy which is actually available after final conversion to the consumer for the respective use.

In final conversion, electricity becomes for instance light, mechanical energy or heat. Figure 1 illustrates the annual energy consumption for house heating when crude oil and coal are used as primary energy, respectively.

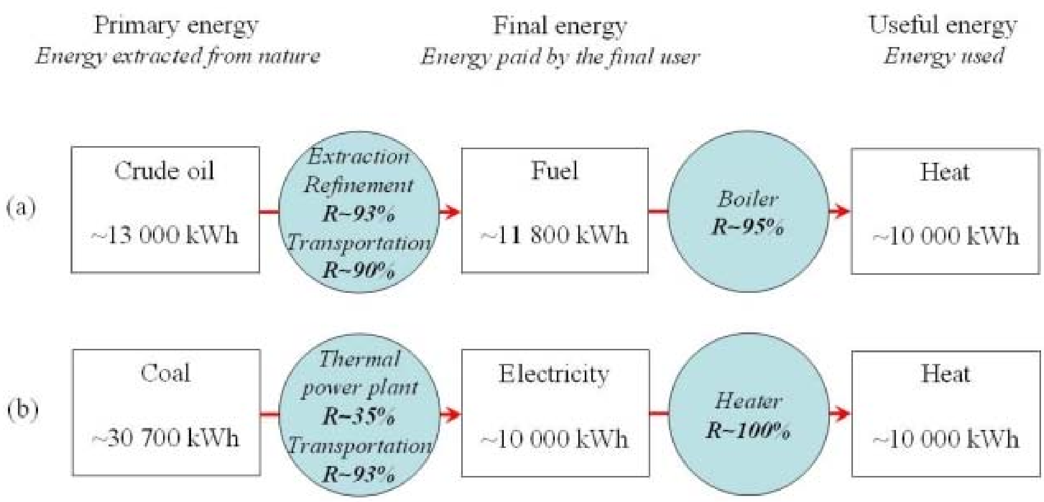

Figure 1. Annual energy consumption for house heating when crude oil (a) and coal (b) are used as primary energy, respectively. R is the conversion or transport efficiency.

On average, the power of typical household devices are 1400 W for heating, 340 W for hot water production, 140 W for cooling and refrigeration, 140 W for lighting, 110 W for washing and drying 110 W for cooking and 70 W for other electric load. As elements of comparison, windmills produce from few kW to 6 MW (most large wind turbines produce between 1 and 3 MW), photovoltaic solar plants from few hundreds W to 20 MW, thermodynamical solar plant from 2 to 350 MW and hydro-electrical plants few kW to 3000 MW (record is 22400 MW at the 3 gorges dam in China). Nuclear plants generally contain four to six reactors. The power of one reactor is around 900 to 1300 MW.

2. Basic Knowledge in Geophysics for Energy Resource Evaluation

2.1. Earth Energy Budget and Atmospheric Motion

Light from the Sun falls on Earth. Per year, the Earth receives from the Sun 8380 times the total worldwide energy consumption (11 billions toe) whereas France receives 200 times its annual energy consumption (250 millions toe). Some of that light reflects off clouds back into space. Some of the light makes it to the ground and warms the Earth.

The warm ground and oceans give off infrared radiation, which is felt as heat (Fig. 2). That infrared radiation moves back up through the atmosphere. Most of it is trapped by greenhouse gases, which keep Earth warm, and with time leaks back out into space. The average energy from sunlight at the top of Earth's atmosphere is around 341.3 Wm^{-2}. Less than half of the incoming sunlight heats the ground. The rest is reflected away by bright white clouds or ice or gets absorbed by the atmosphere.

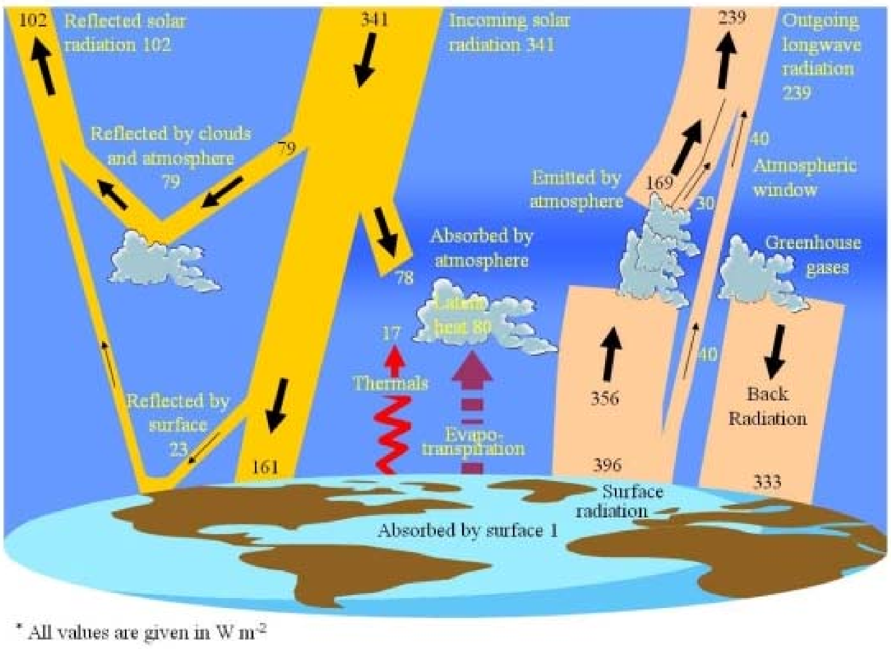

Figure 2. Schematic of the Earth energy budget

The Sun heats the equatorial regions much more than the polar regions. This generates a heat transport from the Equator (region of heat excess) to the poles (regions of heat deficit) which, because of Earth rotation develops in the form of three cells, i.e. the Hadley cell, the mid-latitude (or sub-polar) low and the polar vortex.

The Earth rotates so air travelling southward from the North Pole will be deflected to the right. Air travelling northward from the South Pole will be deflected to the left (this phenomenon is known as the Coriolis effect). This very large scale atmospheric motion is called the global scale atmospheric circulation (Fig. 3). This large-scale structure of the atmospheric circulation varies from year to year, but the basic climatological structure remains fairly constant.

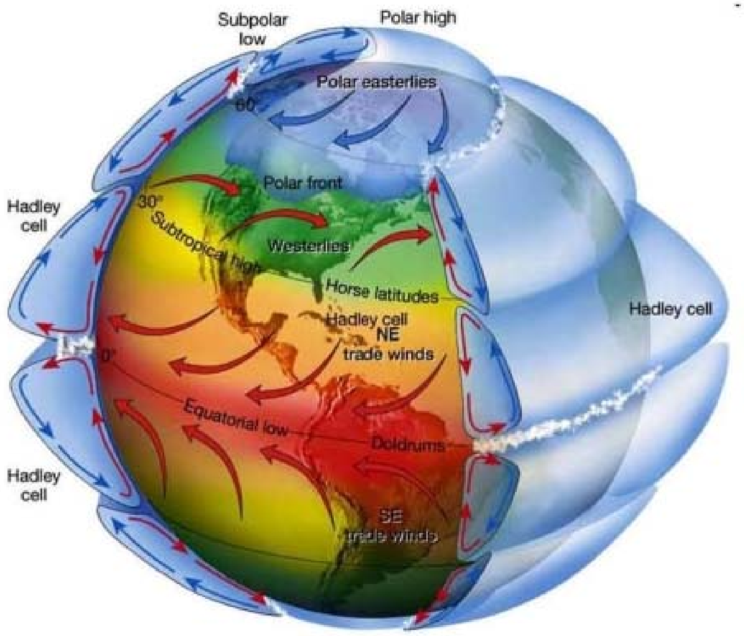

Figure 3. Idealized depiction of the global circulation on Earth (from NASA remote sensing tutorial; courtesy to N.M. Short).

A key feature of the atmosphere circulation is that it covers a wide range of spatial and temporal scales. A spectral analysis of the kinetic energy of the atmospheric flow in terms of spatial wavelength or time period shows that motions of a centimeter spatial scale and few seconds characteristic time coexist with atmospheric flows of several thousand kilometers of horizontal extension and time scale of a few months [7,8].

Between these two extremes, it is possible to find spectral regions relatively less excited that distinguish three broad classes of motions (see Table 1):

1. synoptic-scale circulation of horizontal length scales greater than 100 km and whose time scale is of the order of days. These motions are those that are preferentially studied to forecast weather;

2. micro-scale circulation of horizontal and vertical extension often less than a few kilometers and of time scales ranging from minutes to one hour maximum. This type of motions may be, for example, evidenced by the appearance and disappearance of small clouds;

3. between the two scales above, fairly well differentiated, lies the meso-scale, which is mainly due to the diurnal cycle. Horizontal scales are of the order of tens to hundreds of kilometers while the time scales is of the order of the day. Orographic winds and sea-breezes are good examples of this type of atmospheric circulation.

Table 1 indicates the characteristic time and horizontal distance scales of typical weather events.

Scale of weather events	Characteristic time and horizontal distance scales	Weather events
Micro scale	1s – 100s ; 10 mm – 1 km	Small-scale turbulence; Dust-devil; small cumulus
Meso scale	100s – 1 day ;1 km – 100km	Tornado; Large cumulus; Thunderstorms; Local winds (mountain wind, sea-breeze,…)
Synoptic scale	1 day – 1 week ; 100 km – 10000 km	Fronts; Hurricanes; Anticyclones, Jet stream

Table 1. Characteristic time and horizontal distance scales of typical weather events

It is also possible to characterize the atmospheric circulation by its altitude and/or vertical extension (Fig. 4). At low altitudes, the influence of the ground is predominant and the various heterogeneities induce three-dimensional movements.

The maximum vertical and horizontal extensions are of same order of magnitude of a kilometer. This defines the planetary boundary layer in the troposphere, the preferential region of micro and meso-scale flows.

The planetary boundary layer, also known as the atmospheric boundary layer, is the lowest part of the atmosphere (typically 1-km deep) and its behavior is directly influenced by its contact with the planetary surface. On Earth it usually responds to changes in surface forcing in an hour or less. In this layer, physical quantities such as wind speed, temperature, moisture and pollutants display rapid fluctuations (turbulence) and vertical mixing is strong.

At higher levels, the influence of the ground almost vanishes, the gravity plays a dominant role and the flow becomes quasi two-dimensional. At these altitudes, in the free troposphere, the horizontal extension of the atmospheric circulation is generally very large and corresponds to the synoptic scale.

The wind is approximately geostrophic. The geostrophic wind is the theoretical wind that would result from an exact balance between the Coriolis effect and the pressure gradient force. This condition is called *geostrophic balance.*

It is not met at low levels (typically between the surface and 1-km height) because of ground friction. The geostrophic wind is directed parallel to isobars (lines of constant pressure at a given height), thus explaining the vortex like atmospheric circulation around regions of low surface pressure (cyclones) or high surface pressure (anticyclones).

The meso-scale is intermediate and is in fact the connection between the two scales described above. It includes the weather phenomena of relatively large extension both along the horizontal and vertical and it is not possible to characterize them by a purely two-dimensional dynamics.

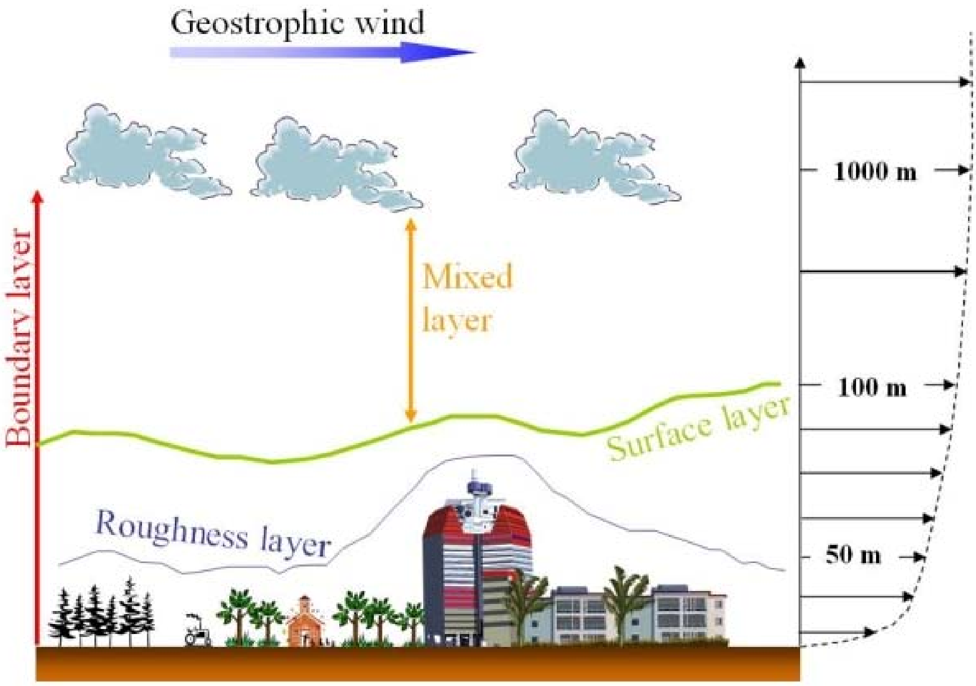

Figure 4. Schematic of the vertical profile of the horizontal wind speed.

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Biographical Sketch

Philippe Drobinski is a French senior scientist at the Institut Pierre Simon Laplace (IPSL) and associate professor at Ecole Polytechnique (Palaiseau, France). He is a specialist in atmospheric boundary layer meteorology, including process studies and regional characterization. He is the author of more than 80 articles in international peer-reviewed journal and is the chair of the IPSL group on regional climate and environment. He is also the coordinator of the Hydrological cycle in the Mediterranean Experiment (HyMeX), international program endorsed by several programs of the World Meteorological Organization (WMO) which aims at a better understanding of the hydrological cycle in the Mediterranean and associated social vulnerability issues. He is editor for Annales Geophysicae, journal of the European Geophysical Union. Philippe Drobinski teaches boundary layer meteorology and geophysics applied to renewable energy resource evaluation at undergraduate and graduate levels.