LECTURE - ALTERNATIVE RESOURCES

We have so far only considered fossil fuel resources. To complete our review of available energy resources we now need to look at alternative/renewable/environmental sources.

E.g. wind, waves, water, solar and so on.

We can no longer use the same method of resource estimation we used for fossil fuels as the resource is not finite and exhaustible but continuous.

A resource can be estimated in terms of its potential throughput, denoted by S. This is generally a function of how much we are prepared to pay, S(£). S(£) is usually expressed as the cost per unit of installed capacity.

However these sources tend to provide much less than their rated capacity. Again I'll quote 3 numbers:

S_1 = indication of present installed capacity

S_2 = indication of ultimate realisable power available

S_∞ = power associated with natural energy flow

"Top down" and "bottom up" estimates of these figures will be given and an idea of the ground area or power density required to realise the resource estimated.

HYDROELECTRIC POWER

This obvious resource has already been widely exploited.

The hydrological cycle is driven by about 1300 Q/y, at first sight it could be our salvation.

However, in the course of the cycle water is evaporated, needing latent heat of 2260 kJ/kg

The vapour is then raised against gravity before forming a cloud.

e.g if cloud height is 2 km then gh = 20 kJ/kg is required.

Latent heat is released during condensation and energy is lost during rainfall.

We can only utilise the energy release of water flowing down the world's rivers. Across the globe this is further reduced by precipitation over seas and Antarctica.

Here is a rough "top down" estimate:

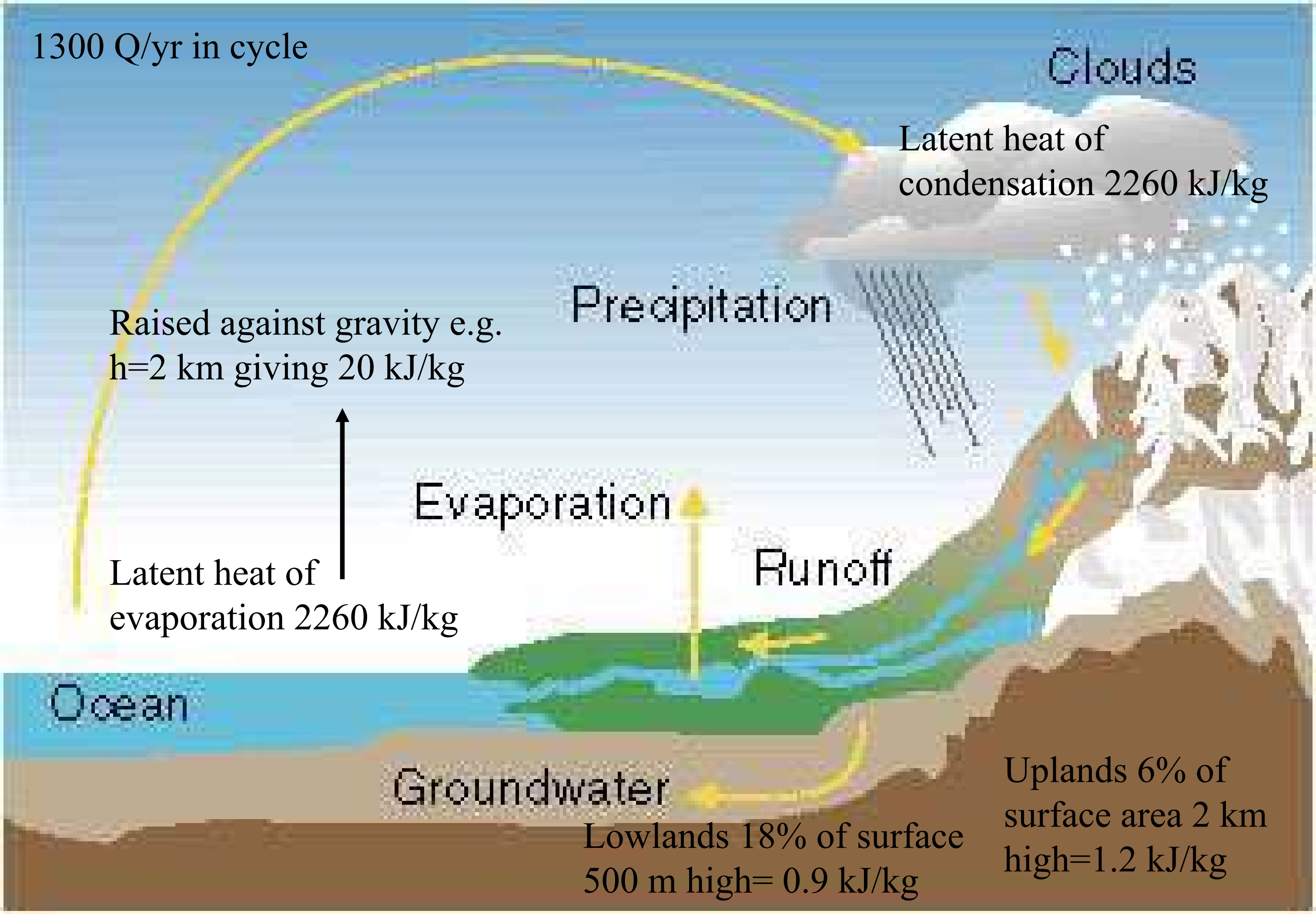
Excluding Antarctica 24% of world's sea area is land and only 25% of this is >1000m.

Taking average value of lowlands = 500 m and uplands = 2000m

Then 18% of worlds area gives at most 5 kJ/kg and remaining 6% gives 20kJ/kg.

We have (5x0.18 + 20x0.06) = 2.1 kJ/kg or 0.1% of input to cycle giving **1.3Q/year**.

HYDROELECTRIC POWER 2



So can utilise 2.1 kJ/kg of 2280 kJ/kg input to cycle so around 0.1 % giving 1.3 Q/year

HYDROELECTRIC POWER 3

Obviously we will not be able to collect all this energy.

The best realistic estimate of the ultimate capacity comes from surveying all possible sites and then summing them up (“bottom up”).

This gives a figure of around $S_2 = 0.1$ Q/year.

Of this about 10% is already installed.

Comparing the “top down” and “bottom up” estimates we are only out by one order of magnitude.

This gives us some confidence in our result.

We are certainly doing well if we can collect 10% of an environmental resource of this kind.

Further exploitation may lead to serious environmental problems. Intrusion of wilderness areas, displacement of local populations, alteration of local climate and effects on downstream river flow.

See the Chinese 3 rivers project for an example of the difficulties of creating such a scheme.

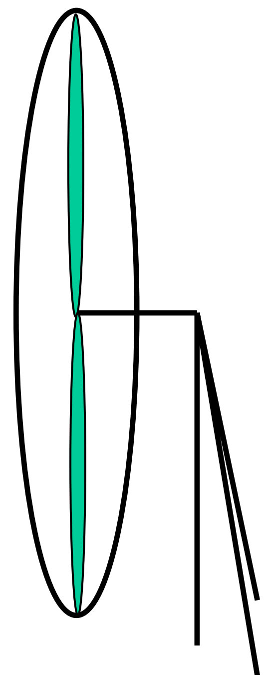
WIND POWER

Wind speed u

Energy density of wind = $1/2\rho u^2$

Energy density delivered at velocity u

So power per unit area = $1/2\ \rho u^3$



Air flows through a collector of area $A = \pi r^2$.

So power delivered to collector is

$1/2 A\rho u^3 = 1/2\pi\rho r^2 u^3$

We cannot bring all the air to rest so cannot harness all delivered power

Efficiency, ε

Theoretical maximum = 59%

Practical maximum = 35%

However the wind is very variable and most of the power is obtained in the less frequent windy conditions. We do not often measure $\langle u^3 \rangle$, however, it turns out that $\langle u^3 \rangle \sim 2\langle u \rangle^3$.

So power produced by a generator is $\varepsilon\rho A\langle u \rangle^3$

WIND POWER 2

Where is Wind Power useful? (Two examples)

University of Manchester Sackville Street Roof:

The average wind speed is around 10 mph ~ 4.5 m/s

Density of air = 1.3 kg/m^3 so power per unit = 41 W/m^2

Assuming 35% efficiency

ORKNEY (Burgar Hill):

The average wind speed is around 30 mph ~ 13.4 m/s

So power per unit = 1.1 kW/m^2

Assuming 35% efficiency

Consider a large wind turbine installed on Burgar Hill, Orkney. It has blades 30 m long.

Swept area ~ 2800 m^2 so total power ~ 3.1 MW.

The same installation on the Sackville Street roof would have a power of 114 kW.

A gas fired power station has about a 2000 MW capacity so would need 650 such machines on Orkney and 17500 of them in Manchester.

WIND POWER 3

Blot on the landscape?

It is important to consider the power density of such a wind farm. Or put another way to have some idea of the area such a farm takes up.

A set of turbines cannot be sited very close together and a rule of thumb is that the spacing must be about 10 diameters.

So in the previous examples one turbine with 30 m blades will occupy an area of 0.6 km^2.

So siting these turbines in:

ORKNEY gives a power density of $3.1/0.6^2 = 8.6$ MW/km^2

A 2 GW power station would then require a site of 230 km^2 or 15 km x 15 km

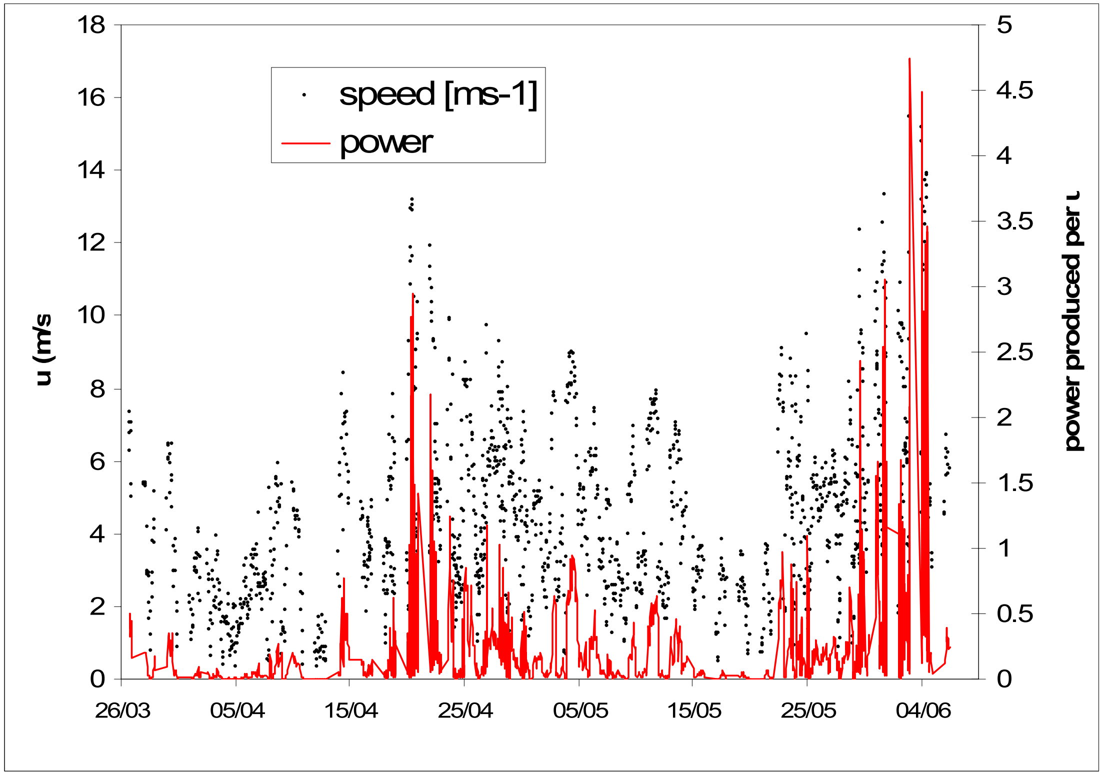
MANCHESTER gives a power density of $0.11/0.6^2 = 0.3$ MW/km^2

A 2 GW power station would then require a site of 6600 km^2 or 81 km x 81 km.

Other activities can take place in such an area but you can see the scale of the problem. For a large scale facility our figure of 9 MW/km^2 is optimistic, a lower estimate of 1.4 MW/km^2 is more usual.

WIND POWER 4

The following graph shows the wind speed at Holme Moss on the Pennine Ridge east of Manchester. Close by is a wind farm of turbines of similar size to the Orkney utility. Taking 35% as the efficiency the time series of the delivered power is also plotted for each turbine:



The total electrical power generated also varies on a diurnal, weekly and seasonal basis but is no way matched to the wind. It turns out that around 20% of average electrical power can be generated by wind farms with little problem, above this short term storage of electricity is essential.

WIND POWER 5

Sites for Wind Farms

Obviously good wind farm sites require the local average wind speed to be high.

Sites are ideally exposed and often in wilderness areas, this can lead to several potential problems:

- intrusion to the countryside
- noise, TV interference
- unsightly

Anywhere in the UK there is likely to be local opposition; offshore in shallow waters may be an alternative.

An ideal offshore site would be away from shipping lanes in an area of high wind speed.

A survey in 1985 pinpointed several likely wind farm locations that were estimated to yield as much power as is currently supplied through the national grid.

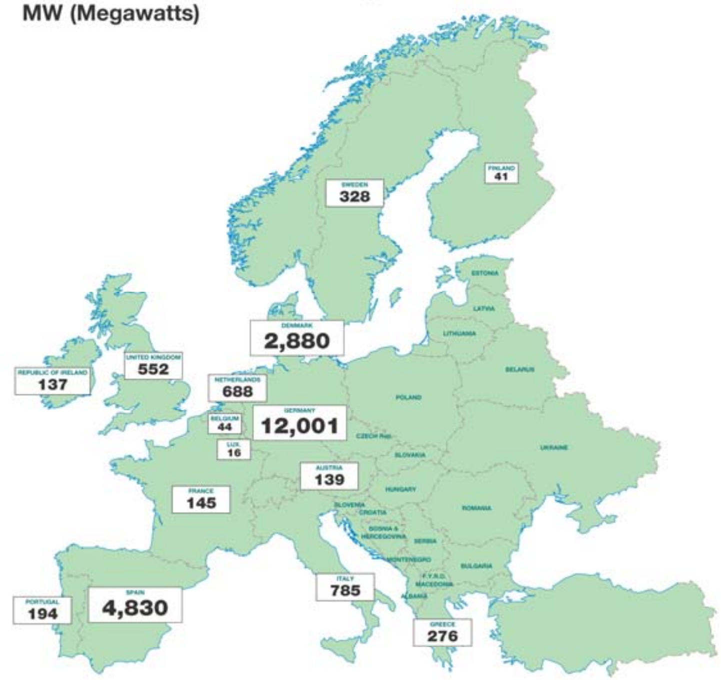
In the US land based systems can do better, the mid west States of the US have the potential to generate more electrical power than is presently consumed in the entire USA.

South Dakota alone could produce up to 1/3 of this figure and hardly anyone lives there.

WIND POWER 6

At a glance						
Projects	**Turbines**	**Megawatts**	**Homes Equivalent**	**CO_2 reductions**	**SO_2 reductions**	**NO_x reductions**
81	**1009**	**559.8**	**365,000**	**1,270,000 tonnes**	**14,600 t**	**4400 t**

Wind power installed in the EU by the end of 2002
MW (Megawatts)



Country	Installed during 2002 (MW)	Total installed by end 2002 (MW)
Germany	3,247	12,001
Spain	1,493	4,830
Denmark[1,2]	497	2,880
Netherlands[1]	217	688
Italy	103	785
UK[1]	87	552
Portugal	63	194
France	52	145
Austria	45	139
Sweden	35	328
Ireland	13	137
Belgium	12	44
Greece	4	276
Finland	2	41
Luxembourg	1	16
European Union	**5,871**	**23,056**

1 Decommissioning of wind power capacity: Denmark (106 MW), Netherlands (15 MW), UK (9 MW).
2 There is a discrepancy in the utilities' reporting system which could reduce the Danish figure for installation during 2002 by 45 MW to 452.

EWEA
www.ewea.org
Source: European Wind Energy Association 6 February 2003

WIND POWER 7

ESTIMATES ON A GLOBAL SCALE:

This isn't so easy. Here, onshore and offshore sites are treated separately.

The previous estimate for the US allows us to make a "bottom up" estimate for inland areas.

The electrical power consumption in the US is currently 0.01 Q/year.

We can assume that all of this can be supplied by wind energy and the rest of the world on average is about as well placed as the US for utilising this resource. Then, as the US is about 1/17 of the world's land area

Total = 0.17 Q/year

We can also produce a "top down" estimate:

12Q/year are required to drive the atmospheric wind system.

30% of the world's surface is land, in general wind speeds over land are lower than over the sea so we should not allow for more than 15% of the total or 1.8 Q/year as the absolute upper limit.

Two estimates again within a factor of 10. As we saw before a 10% collection efficiency is pretty good going we'll take the lower estimate for S_2 = 0.17 Q/year

WIND POWER 8

GLOBAL SCALE ESTIMATES OF OFFSHORE RESOURCE :

Practically this must be restricted to the continental shelves.

By making a rough estimate of the world shelf (less than 50 m deep) area, and noting that offshore winds are stronger, we can estimate the total power level from the Orkney power density (9MW/km^2).

This yields a possible 0.12 Q/year.

Practically, not more than 20% of this is likely to be exploitable so we can take the final value of S_2 for both types of site on a global scale to be :

0.2 Q/year

WAVE POWER

We can provide a simple "bottom-up" approach to the energy delivered from waves by considering the average power per unit length of waves delivered to a coastline.

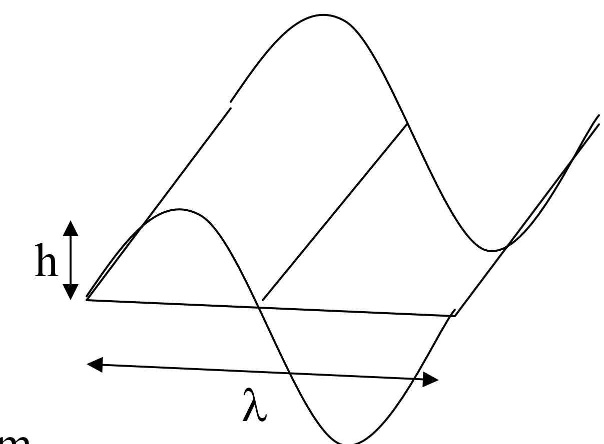
Assume that the group velocity of the waves is: $$c = \frac{1}{2}\sqrt{\frac{g\lambda}{2\pi}}$$

where λ is the wavelength.

Energy of a water wave = mgh/2 where h is the wave amplitude and m is the mass (or similar)

Energy per unit area $U = \rho g h^2/2$ where ρ is the water density

So power per unit length of coastline, F,= $1/4\rho g h^2(g\lambda/2\pi)^{1/2}$



taking typical values of $h \sim 1.5$ m, $\lambda \sim 10$ m then F = 23 kW/m.

WAVE POWER 2

This approach can be used to estimate the power input to the North Atlantic Ocean.

Let us assume that no energy is dissipated by non breaking water waves i.e. all energy dissipated at shoreline.

Hence input power = power delivered to coast.

If we assume that the Atlantic Ocean is a circle of radius, $r \sim 2000$ km then the input power, $W = 2\pi rF = 2.9 \times 10^{11}$ W

This gives power/area input = $W/\pi r^2 = 0.023\ \mathrm{Wm^{-2}}$.

We can then make an estimate of the total worldwide annual wave energy input to Earth

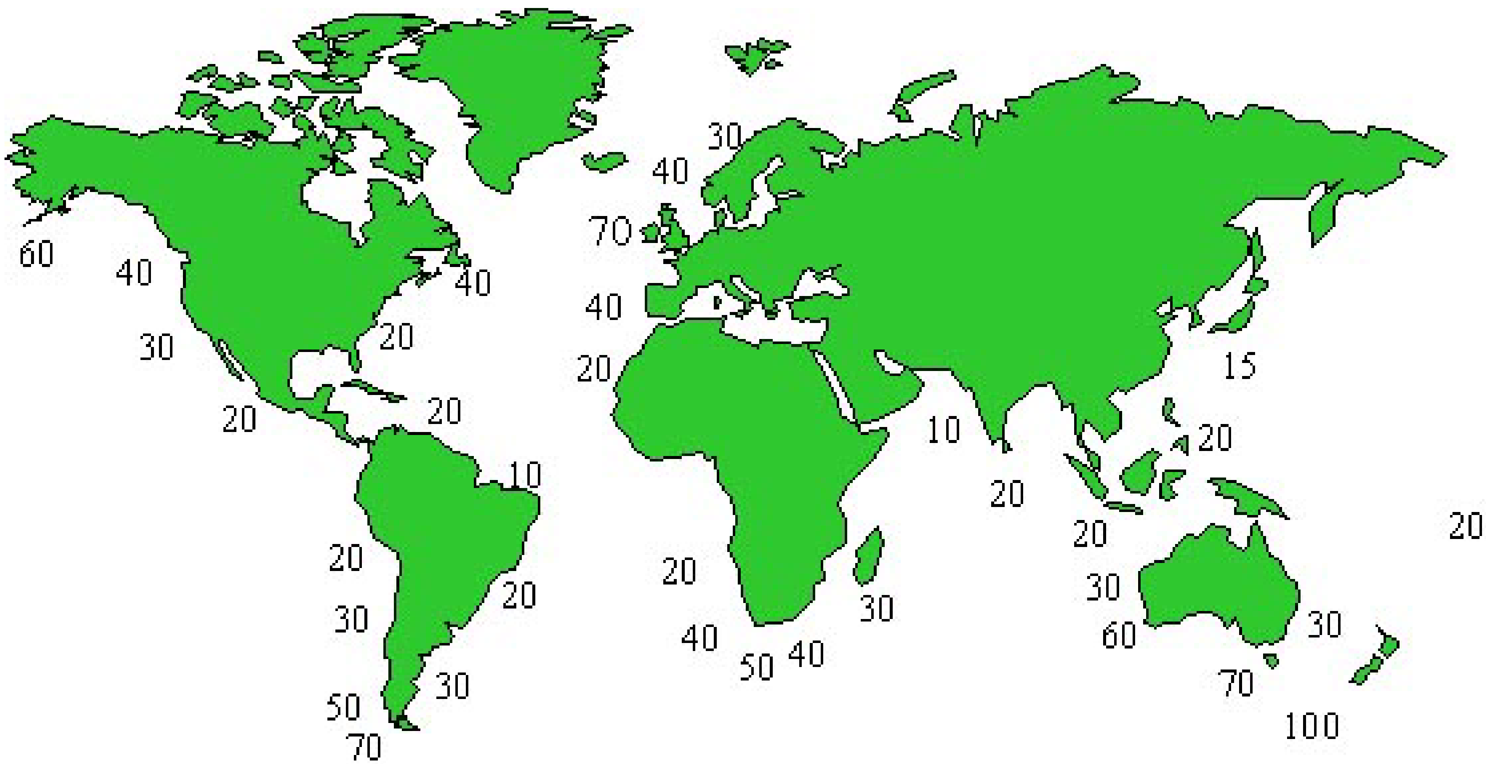
World ocean = 0.7 of world surface, so total wave power = $0.7*\pi R^2$ where R is the radius of the earth. (radius of Earth ~ 6360 km)

Area of ocean = $8.9 \times 10^{13}\ \mathrm{m^2}$.

Total power = 2×10^{12} W

Annual wave energy = 6.5×10^{19} J/year = 0.065 Q/year

WAVE POWER 3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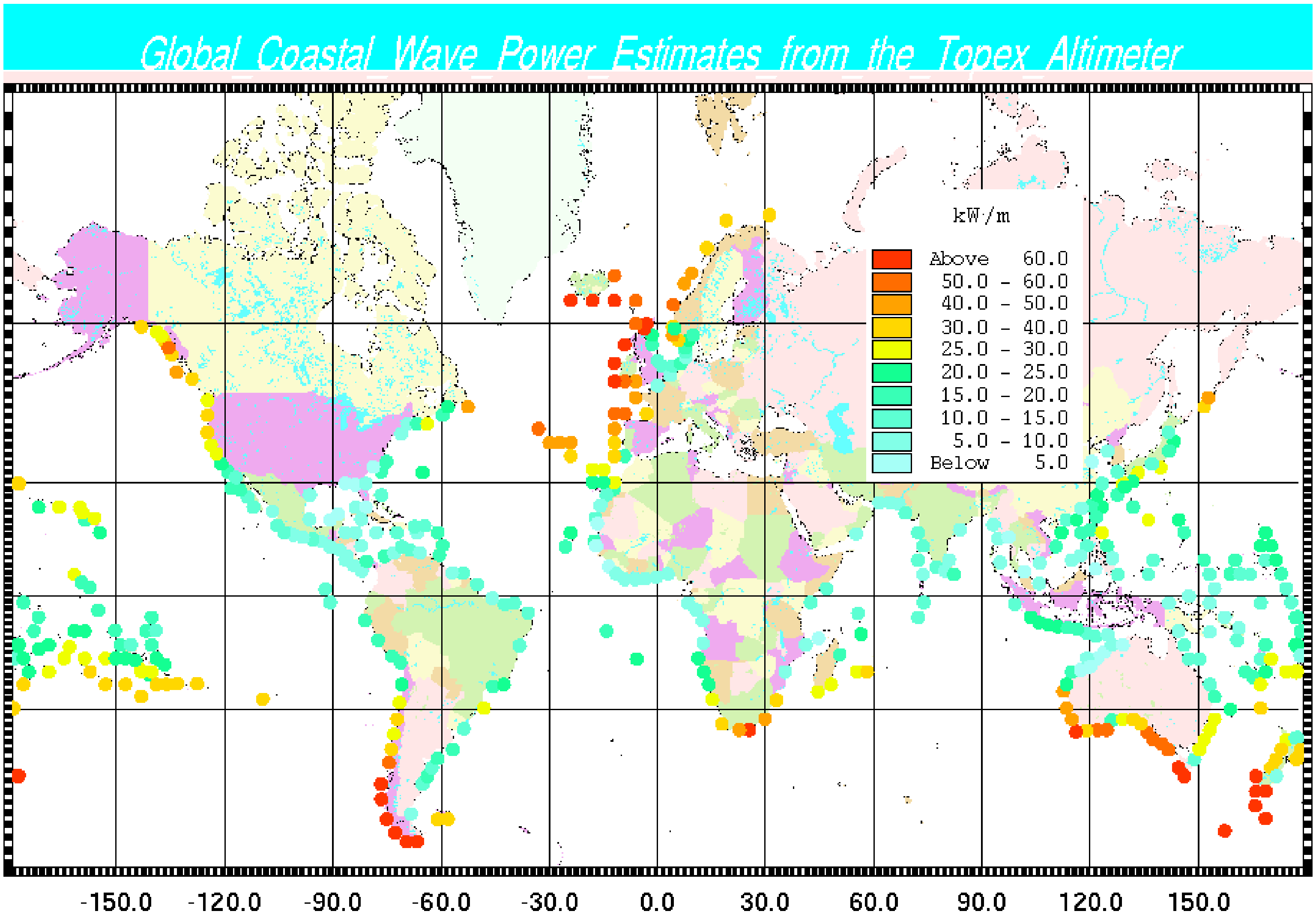
WAVE POWER 4


Global Coastal Wave Power Estimates from the Topex Altimeter
kW/m
Above 60.0
50.0 - 60.0
40.0 - 50.0
30.0 - 40.0
25.0 - 30.0
20.0 - 25.0
15.0 - 20.0
10.0 - 15.0
5.0 - 10.0
Below 5.0
60.0
30.0
0.0
-30.0
-150.0
-120.0
-90.0
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