GLOBAL WIND POWER POTENTIAL, physical and technological limits

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Abstract

This paper is focused on a new methodology for global assessment of wind power potential. Most of the previous works on the global assessment of the technological potential of wind power have used bottom-up methodologies (e.g. Archer and Jacobson, 2005, Capps and Zender, 2010, Lu et. al., 2009). Economic, ecological and other assessments have been developed, based on these technological capacities. However, this paper tries to show that the reported regional and global technological potential are flawed because they do not conserve the energetic balance on Earth, violating the first principle of energy conservation (Gans et al., 2010). We propose a top-down approach, such as that in Miller et al., 2010, to evaluate the physical-geographical potential and, for the first time, to evaluate the global technological wind power potential, while acknowledging energy conservation. The results give roughly 1TW for the top limit of the future electrical potential of wind energy. This value is much lower than previous estimates and even lower than economic and realizable potentials published for the mid-century (e.g. DeVries et al., 2007, EEA, 2009, Zerta et al., 2008)

Key words: Renewable energy potential; wind energy; global energy assessment;

1. Introduction

The limited nature of fossil and nuclear fuels and the socio-ecological problems associated to them are important incentives for a global transition towards renewable energies, which must be accomplished in this century. The wind power and solar photovoltaic technologies are gaining more support as candidates for this transition (Zerta et al., 2008, Greenpeace, 2010, Jacobson, 2009, REN21, 2010, Schindler et al., 2007).

Most studies try to envision scenarios that avoid an abrupt change of the socio-economic global system and, therefore, search for ways to keep increasing energy consumption and relative efficiency while, at the same time, solving such environmental problems as pollution and Climate Change (WEC, 1994, IPCC, 2007, Jacobson, 2009, IEA, 2010).

The great majority of the studies that evaluate the long term technological potential of renewable energies conclude that the amount of renewable resources poses no limit from the technological point of view, due to their extreme abundance. In the particular case of wind energy, the usable power is said to be several times greater than the global amount of total energy used today in the World; therefore, the technological limits are assumed to be unreachable for decades, and the concern is on the economic, political or ecological limits imposed (REN21, 2010, Johansson et al. 2004, Nakicenovic et al. 1998, Greenpeace, 2008)[1].

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[1] "Renewable energy resources are immense and will not act as a constraint on their development" (Johansson, 2004). "The world has tapped only a small amount of the vast supply of renewable energy resources" (REN21,

Section 2 reviews the estimations of global wind power resources present in the literature. Section 3 calculates the global technical potential of wind energy using a top-down methodology. In section 4, we demonstrate that the estimations of wind potential based on a bottom-up approach are not coherent with the energy conservation principle and finally, in section 5, conclusions are extracted.

2. Previous estimations of the technical potential of wind energy

Several authors have estimated the geographical, technical and economic power available in Earth's wind energy . Table 1 summarizes the main results found in the literature.

If we take a look at the economic and sustainable potentials they establish, Schindler et al. (2007) and Zerta et al. (2008), for instance, estimated 6.9TW as the plausible development during this century. On the other hand, Graßl et al., (2003), established 4.5 TW as the economic and sustainable potential of wind energy during this century, DeVries et al. (2007) gives 4.5TW for 2050, while EEA (2009) envisions, only for Europe, a potential of 3.5TW as soon as 2030. Greenpeace (2008) projects scenarios with 1TW for 2050 and cites studies of several authors with sustainable potentials of 15TW. All of these economic or sustainable assessments are based on technical potentials while adding more restrictions; therefore, technical global potentials are higher. As we shall see in section 3, the technical potential we estimate in this paper is one or two orders of magnitude lower than most of these technical potentials, in fact, it is lower than the estimated economic and sustainable potentials cited in table 1.

Authors	Technical power (TW)	Economic/sustainable power (TW)
Archer, Caldeira 2009	1500 (jet stream, % feasible?)	
Archer,Jacobson 2005	72 (onshore)	
Capps, Zender, 2010	39 (offshore)	
DeVries et al. 2007		4.5 (in 2050)
EEA 2009	8.6 (Europe)	3.5 (Europe 2030)
Graßl et al. 2003	32 (global)	4.5 (sustainable)
Elliott + Musial 2005	1 (EEUU)	
Greenblatt 2005	70.4 (global)	
Greenpeace 2008 Greenpeace 2010		1 (in 2050) 1.2 (in 2050)
Grubb, Meyer 1993	57 (global)	
Hoogwijk et al. 2004		10 (economic)
Lu et al., 2009	78 (onshore), >7 (offshore)	
McElroy et al. 2009	0.7 (China)	
Miller et al., 2010	17-38 (onshore, geographical potential)	
Schindler et al. 2007		6.9 (sustainable)
Smil 2008	< 10 (global)	
WEC 1994	55.2 (global)	

2010). "They can provide energy for any level of future energy demand" (Nakicenovik et al., 1998). "In summary, wind power is a practically unlimited, clean and emissions free power source" (Greenpeace, 2008)

Wijk, Coelingh 1993	2.3 (onshore, OCDE)	
Zerta et al. 2008		6.9 (sustainable)

Table 1. Feasible power of wind according to several authors. Most technical powers are primary power, not electrical.

All of these studies that evaluate the technical power potential of wind energy (see table 1), except the one by Smil, (2008) (with no explicit methodology) and the one by Miller et al. (2010) that calculates a physical-geographical potential, use a bottom-up methodology: they take the wind speed in many locations of the Earth surface, exclude the areas that are considered not suitable for wind farms, and calculate the energy that would be trapped in those locations with the technically available present or future windmills.

3. Estimation of technical potential of global wind energy

A top-down methodology would be based on the following steps: we must first take into account the global amount of power available as kinetic energy of the wind in the atmosphere, P_0, and in the lower atmosphere (altitude lower than 200m), usable by windmills, $P_0(h<200)$. This power must be reduced by the geographical constraints, which account for the percent of land suitable for wind farms (excluding, for instance, remote and frozen land areas and deep sea surface). We shall call P_G, the geographical potential, the power available after the geographical constraints are considered.

The technical potential, P_T, is more restrictive than P_G and takes into account the energy that the windmills can extract, considering current or plausible technological efficiencies. Economic power P_{Ec} is even lower and considers the restrictions derived from the costs of the technology, and finally, if the disturbances in the ecosystems are taken into account, we end up with the estimation of the sustainable power P_e, which shall be the limit that we should not surpass in order to preserve the health of the planet (see for instance DeVries et al. (2007) for similar definitions).

In order to calculate the global potential of wind energy, we use a top-down methodology based on six stages. The base data is the kinetic energy contained in the atmosphere, and this amount is restricted by several constraints that subtract the energy that cannot be transformed into electricity. These constraints are:

1. The energy of the lowest layer of the atmosphere, f_1, $P_0(h<200) = f_1 \cdot P_0$
2. Reachable areas of the Earth (geographical constraint), f_2. $P_G = f_1 \cdot f_2 \cdot P_0$
3. Energy of the wind that does interact with the blades of the mills, f_3
4. Energy of the areas with reasonable wind potential, f_4
5. Energy of the wind speeds that are valid, f_5
6. Efficiency of the conversion of kinetic energy into electric energy, f_6

$P_T = f_1 \cdot f_2 \cdot f_3 \cdot f_4 \cdot f_5 \cdot f_6 \cdot P_0$

Global kinetic energy of the atmosphere.

According to several authors, the kinetic energy that wind contains and is dissipated into other forms of energy varies between 340 and more than 1200 TW (e.g. Gustavson (1979), 3600TW, Lu et. al., (2009) 340TW, Lorenz (1967) 1270TW, Wang and Prinn (2010) 860TW, Peixoto and Oort (1992) 768TW, Skinner (1986) 350TW, Sorensen (1979 y 2004) 1200TW, Keith et al. (2004) 522TW). These data are obtained using global thermodynamic models of the solar irradiation on Earth. Some consider the entire atmosphere, while others restrict it to altitudes lower than 1000m.

In our study, we will take the one of Sorensen, (2004), P_0 = 1200TW, because it is for the entire atmosphere and also gives turnover times of kinetic energy.

f_1, the energy of the lowest layer of the atmosphere.

Not all the wind of the atmosphere can be captured with windmills, only the one that is closest to the Earth's surface. The biggest windmill today (as of October 2010) has a power of 7.6MW, the diameter of its blades is 126m and is 198m high (Enercom, 2010). Although in future years the size of windmills might continue to grow, most of the mills installed today have diameters below 90m (less than 2MW), and those installed to date will continue in their locations at least till 2030. Therefore, we will consider that, at least during this century, the windmills will have an average size of 200m, and therefore, the layer of atmosphere whose energy can be extracted is that of the 200 meters closest to the Earth's surface. Therefore, we are interested in an estimation of the percent of the wind energy and power of the atmosphere that is contained in those first 200m. We use several methods to estimate and calculate this power: the first one based on the energetic density of the atmosphere, the second based on the residence time of winds and a third based on the Boundary Atmospheric Layer wind power.
The energy density of air increases with height, from 30 J/m^3 at 100 m to more than 120 J/m^3 at 5000m, because the energy is dissipated at a higher rate where there is more friction, close to the ground (Sorensen, 2004). In the layer below 200m, the dissipation rate is around 4 times higher than above one kilometer (Sorensen, 2004). If 1200TW are dissipated in 10000m of atmosphere (troposphere), in the first 200m, and considering a dissipation four times greater per unit of volume, there is 12.5 times less power than in all the atmosphere, that is 96 TW.
Another way to estimate the energy of the 200m layer is using the residence time of the wind, which is the average time that its kinetic energy takes to dissipate into heat. We can calculate the kinetic energy of the 200m lowest layer of air based on the mass and speed of this layer. Based on the experimental data and the calculations of Archer and Jacobson, 2005, we can calculate the speed of wind at any height as $v_h = v_{10} \cdot (h/10)^a$, v_{10} being the mean speed at 10 m height (5.8m/s according to Archer and Jacobson, 2005) and "a" a constant (Hellman's exponent) taken as a = 1/7 (Archer and Jacobson, 2005). Using this formula, the mean speed of the winds between 0 and 200m is $v_{\text{mean } 0\text{-}200m} = 7.9$ m/s. The mass of this layer of air can be calculated by taking its density as 1.2 kg/m^3 and the volume as approximately $4 \cdot \pi \cdot R_T^2 \cdot 200 = 1.22 \cdot 10^{17}$ m^3. The mass of the first 200m of air ends up being $m_{\text{atm } 200m} = 1.47 \cdot 10^{17}$kg, therefore, the kinetic energy of the layer of air closest to the surface would be $E_{c\ 200m} = 4.59 \cdot 10^{18}$ J. The residence time of this air, $t_{c\ 200m}$, can be estimated as roughly half a day (lower than the mean residence time in the atmosphere which is 7.4 days), since it is mainly determined by the night-day cycle and the direction and intensity of wind usually varies with that rhythm (Sorensen 2004, Stull, 1988). According to these data, the power dissipated in this layer is $P_{0\ 200m} = E_{c\ 200m} / t_{c\ 200m} \sim 106$ TW, which is similar to the value of 96 TW calculated with the previous methodology.
A third method to estimate this power could be calculated from the dissipated power of the Atmospheric Boundary Layer (ABL). Hermann (2006), gives 290TW to this power. Generally the boundary layer thickness is quite variable in time and space, ranging from a few

hundreds of meters to a few kilometers. If we take the mean thickness of this layer as 400-800m (Stull 1988, Hennemuth and Lammert, 2006), then the first 200 m are between a halve and a fourth of this Boundary Layer with lesser turnover time, but also with lower wind velocities, therefore, approximately between 1/2 and 1/4 of the wind power in the ABL will be dissipated in the first 200m.: 72.5-145TW, again roughly 100TW as the P_0 (h<200) value.

Taking these three methodologies into account, we will take the value of the power dissipated in the layer of air closest to the surface as P_0 (h<200) = 100 TW = $P_0 \cdot f_1$, where

$f_1 = 0.083$

f_2, geographical constraints, reachable areas of the Earth.

Not the entire Earth surface is suitable for kinetic energy extraction: the deep sea areas (more than 200m deep), areas permanently covered by ice, high mountains, cities, protected areas and natural parks, etc., could be excluded by geographical constraints; therefore, more than ¾ of the Earth's surface is not suitable for wind farms (Archer and Jacobson, 2005, Capps and Zender, 2010, Lu et. al., 2009). On the other hand, the windiest continent is Antarctica, and wind has a lot more energy over the deep seas than on the ground. We could, therefore, easily estimate that less than 80% of the energy will be lost because of these geographical restrictions.

$f_2 < 0.2$

f_3, energy of the wind that does interact with the blades.

Current wind parks are designed leaving a space between mills to prevent efficiency losses due to turbine interference ("Wind park effect"). These distances are typically 4D in the direction perpendicular to the dominant wind and 7D in the parallel direction, with D being the diameter of the blades (Archer and Jacobson, 2005, Capps and Zender, 2010, Lu et. al., 2009). Using optimal distributions of the mills such as this one, the efficiency loss from the wind park effect is reduced to 2-5%.

According to this separation between turbines, a wind front 200m in height that would go through turbines of 125m in diameter and 200m high, would not intersect any blade in 60% of the rectangular surface that it occupies. Plus, the necessary separation between mills means that, roughly, more than 25% of the incident wind cannot go through any turbine. This means that a wind farm might try to catch less than approximately 30% of the kinetic energy that goes through it, because the rest will simply never interact with the blades of the mill (see figure 1). Therefore:

$f_3 < 0.3$

Figure 1. In a wind park, the catching surface of each mill is S_1. If the mills are all in a horizontal plane, each mill occupies a surface of the wind $S_1 + S_2$, where S_2 is the surface not brushed by the blades. On the other hand, even if the park has several lines of turbines, there will be a surface, S_3, between mills where the flow of the wind is free. Therefore $f_3 = S_1 / (S_1 + S_2 + S_3)$.

f_4 energy of the areas with reasonable wind potential.

Even in locations accessible and suitable for wind parks, it is reasonable to think that not all of them will be occupied by wind parks, but the mills will be restricted to those areas with the highest wind power. Today the areas are classified, according to wind power, into different classes. Most parks today are in areas of class 5 or 6, since they are the most profitable technically and economically, since, in order to produce the same energy in a park with wind of class 3 we need two times more mills than in a park of class 6. We consider that the mills will be situated in areas of class 3 or higher (as in Archer and Jacobson, 2005). According to the study of Archer and Jacobson (2005), approximately half of all the kinetic energy of the geographically accessible areas are in areas of class 3 or higher (more than 75% of the areas are of class 1 and 2, although they carry a lot less energy per km^2). Using this estimation and considering that only locations of class 3 or higher would be used we have:

$f_4 = 0.5$

f_5, energy of the wind speeds that are valid.

Although wind turbines today are designed for a wide range of speeds, they have a limit on the highest and lowest speed they can use (typically between 2.5 m/s and 25 m/s) and they are designed to give the maximum power in a particular spectrum of speeds. This means that during many hours of the year the turbine does not produce energy that does exist. Since the power of the wind grows with the cube of its speed, if the turbine is designed to give the maximum energy at 12 m/s, for example, at 20 m/s it wastes more than 75% of the wind energy. Modern turbines can interact with less than half of the energy that goes through them. We estimate that future designs will be able to improve this ratio and use three quarters of the energy that interacts with them, but not much more, therefore:

$f_5 = 0.75$

f_6 efficiency of the conversion of kinetic energy into electric energy.

A windmill can transform into electric energy at most 59% of the kinetic energy that it catches (Betz law). There are also losses in the blades, in the alternator, in the power converters and also losses due to maintenance and failures that the mill might have throughout its life time. Today, the electric rate of mills is approximately one third, if we assume that it improves in the future and gets close to the limit of Betz law, we can assume that:

$f_6 = 0.5$

Taking into account all these limitations and the global kinetic energy of the atmosphere calculated in this section, we can estimate that the final technical potential of the wind is:

$P_T < P_0 \cdot f_1 \cdot f_2 \cdot f_3 \cdot f_4 \cdot f_5 \cdot f_6 \sim 0{,}0009 \cdot P_0$

$P_T\ (h < 200) \sim 1\text{TWe}$

One of the criticisms that we could pose concerning our own methods comes from the fact that, although there are no commercial turbines higher than 200m, some scientific literature is speculating with apparatus that would trap the energy at high altitudes (>500m) (Archer and Caldeira, 2009, Fagiano et al. 2009, Roberts et al., 2007).
These future technologies would be subject to many of the restrictions that we have calculated for low height, and the principal restriction would be given by the factor f_3, the energy of the wind that does interact with the blades. All of the designs of these technologies are attached to the ground, and the ones with greater perspectives are the helicopter and tie types (see figure 2). Since the wind fluctuates in direction and intensity, these mobile designs would need an area of operation and security a lot larger than the fixed windmills.

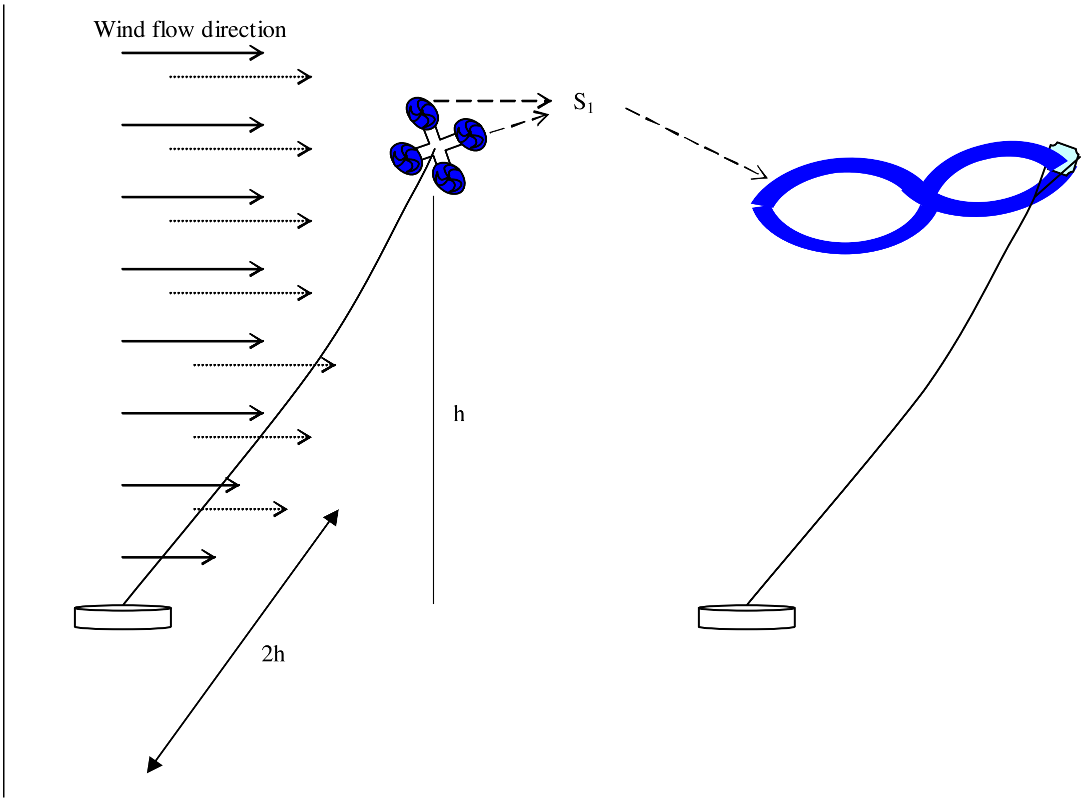

Figure 2. Hypothetical helicopter and tie turbines. If they are at an altitude h, the effective area S_1, in blue, is compared with S_2, the surface of the wind front that does not interact with the tie or helicopter blades, S_2 being roughly $2h \cdot 10000$ (where 10000 m is the thickness of the atmosphere). Even if S_1 is made up of a total array of helicopters or ties of 2000 m^2 and h = 1000 m, $S_2 = 20 \cdot 10^6 m^2$, therefore: $f_3 = S_1 / S_2 = 10^{-4}$

As we can see in figure 2, f_3 will not, for these designs, be greater than 10^{-4}, and because we will also have the rest of the ‘f’ factors, then much less than $10^{-4} \cdot P_0$ could be used from the kinetic energy in the entire atmosphere.

4. Criticisms of the bottom-up methodologies.

Bottom-up methodology should take into account that each time a wind front goes through a turbine it reduces its speed and power (wake effect, Christiansen and Hasager, 2005). According to Christiansen and Hasager (2005), the speed of a wind front is reduced by 8-9% and the power by 25% when it goes through a wind park and does not recover until the next 5-20Km.

In order to regenerate the energy loss by the wake effect at global scale only a huge kinetic energy transfer from above the windmill atmospheric layer could justify partially a bottom-up approach. But Wang and Prinn (2010) (see also Keith et al., 2004) use a general circulation climate model and shown that the kinetic energy per unit mass in the atmospheric boundary layer is reduced by more than 10% in order to generate 5 TW of electric power globally.

Climatic change and land use change (mainly deforestation and reforestation and buildings and urbanization) are causing changes in the winds velocities distribution over Earth. Wang and Huang (2004), give a 20% increase of the wind energy input to the surface waves in the last half century and, on average, terrestrial near-surface winds have slowed down in recent decades (McVicar and Roderick, 2010); human induced surface rougness changes are effectively reducing wind energy and changing wind distribution, therefore windmills will do.

All these facts should be considered when using bottom-up methodologies, since they would significantly reduce the effective density of windmills in the suitable areas; but these considerations are not found in the authors of table 1 (except for Miller et al. 2010, who uses a top-down methodology). These studies assume that the perturbation that a wind farm produces is negligible compared to the global amount of resource; but that bottom-up methodologies are not compatible with global data of kinetic energy present in the atmosphere and therefore violate the principle of energy conservation as Gans et al. (2010) does explicitly on theoretical grounds based on the wake effect, and Wang and Prinn (2010) does implicitly using a 3D general circulation model.

In order to demonstrate that the bottom-up methodologies that many authors use to estimate the potential of wind energy are not valid let us use the results of table 1 and section 2.

We are going to use the factors f_1 to f_6, calculated in section 2, and do the inverse calculation: using the technical potential estimated by these authors to find the amount of kinetic energy that they would require from the atmosphere. If the energy required is greater than the global kinetic energy contained in the wind (1200 TW, as discussed in section 3) the estimations are incoherent.

If we take into account the 72 TW that Archer and Jacobson (2005) consider feasible for just onshore wind potential, and add all the wind energy discarded because of impossible locations, >80% (see section 3), the energy discarded because of low average speed (25%), the energy not used because of wrong speed (50%) and the interaction of the front with the blades (75%), we would conclude that the global kinetic energy dissipated by the atmosphere in the 200 m closest to the surface should be higher than 4000TW, a lot higher than the 100 TW of energy that we estimated for the layer of 200m closest to the surface, and even larger than the estimations of 1200TW for all the energy dissipated in the entire atmosphere.

In Capps and Zender (2010), they estimate a technical potential of 39 TW of offshore energy by occupying locations that, they say, carry only 2.73% of the kinetic energy of the sea winds and using mills of 80m in diameter and a capacity factor of 0.5. Using their own calculations, we would end up estimating that 7500 TW are carried by all the oceans in the 200m layer of atmosphere close to the surface, six times greater than the estimation of the kinetic energy of the entire atmosphere.

5. Conclusions

The global assessment of the technological potential of wind power, based on the top-down approach, shows quite different results to those of previous works. The technical assessment potential that has been obtained is one or two orders of magnitude lower than those estimated by authors referred to in table 1, and is only comparable to the estimation by Smil, 2008 (<10TW), except for the physical-geographical potential estimated by Miller et al. (2010), also using a top-down methodology, which is 17-38 TW (our physical-geographical potential applying only f1, f2 and f6, which is comparable to Miller et al. (2010)'s methodology and calculations, would be <40 TW). This means that technological wind power potential imposes an important limit to the effective electric wind power that could be developed, against the common thinking of no technological constraints by economic, ecological and other assessments.

According to the World Wind Energy Association (WWEA, 2010), the electrical wind power produced today is ~0.045 TW and this type of energy is growing at an annual rate of >25%. If the present growth rate continues, we would reach the 1 TW we estimated in less than 15 years. Therefore, probably in this decade, we will see less growth than we saw in the previous decade.
This limit poses important limitations to the expansion of this energy. Since the present exergy consumption of all energies is ~17 TW, it implies that no more than 6% of today's primary energy can be obtained from the wind.

On the other hand, transforming 1 TW of wind energy into electricity requires 10^{12} m^2 (taking required land of 1 W/m^2, Smil, 2010). This amount represents more than 5% of the land dedicated on the Earth to agricultural land ($1{,}5\cdot 10^{13}$ m^2), which is a very significant impact on the landscape and the ecosystems, even if the space of the wind parks can be dedicated to other uses too.
Furthermore, if the electric wind power of the world were to approach 1TW, we could generate a new class of "tragedy of the commons" (Hardin, 1968) with the necessity of the international regulation of rights to winds. Without an effective regulation, in a medium-term future, we will see "wind park effect and wake effect" at global scale, making less efficient new and old installed parks.

Global assessment of potential energy based on bottom-up methodologies has been used for renewable energies such as tidal, wave or geothermal. Dubois et al. (2008) is an extreme case (in an undergraduate reviewed paper) that gives more than 3000TW as the resource of waves (158TW as the technical-geographical potential), but the total energy transferred from wind to sea waves is 60TW (Wang and Huang, 2004), and the waves exergy dissipated on sea coast is only 3TW (Hermann, 2006). A top-down methodology must start with this 3TW as the geographic potential, P_G, and then apply their corresponding reduction factors, f_3 to f_6.
A top-down review of the global assessment of potential energy from these renewable sources may be necessary in order to obtain the best estimation for the top limit of primary energy that our society is able to use in a sustainable way.

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