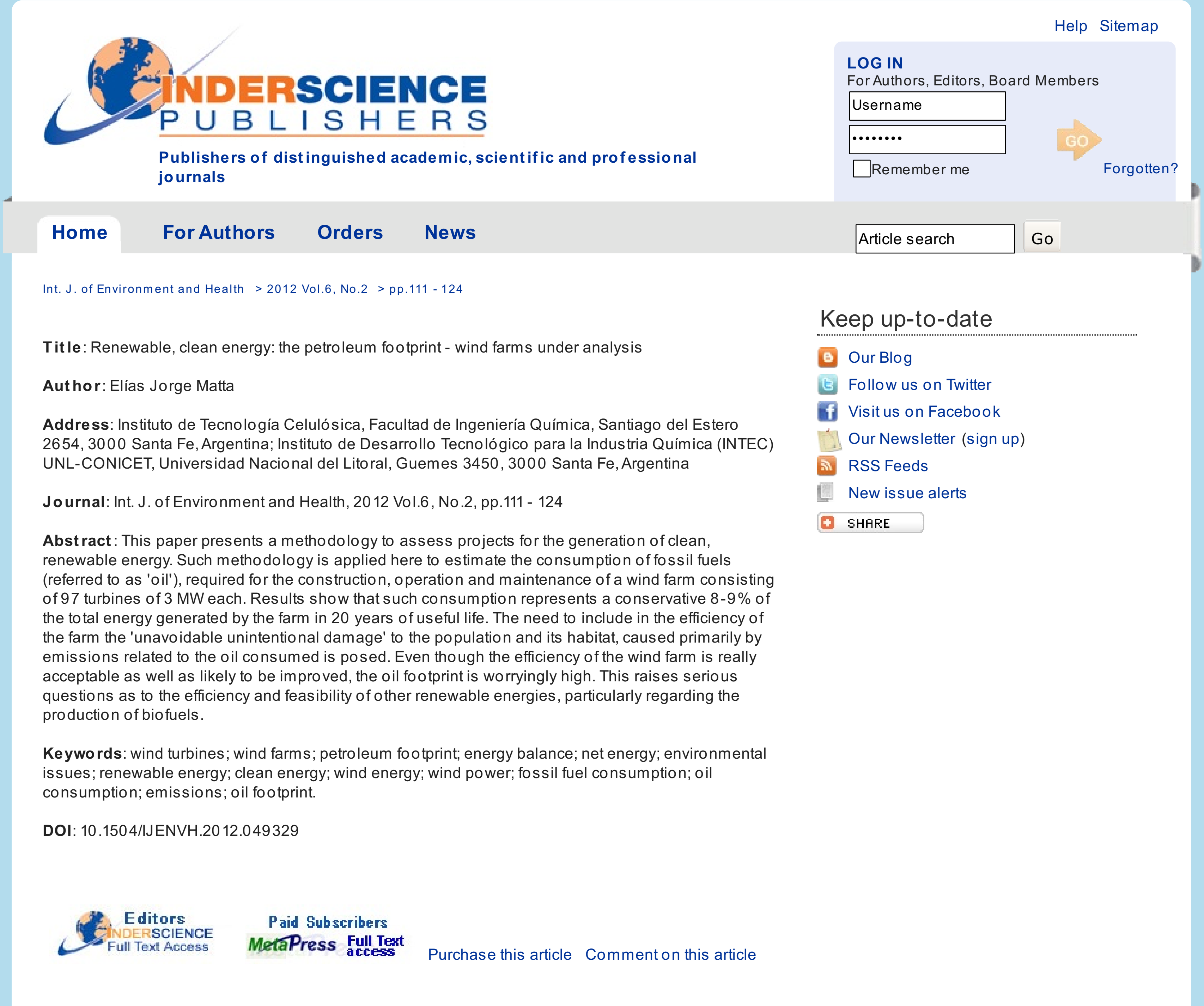

Title: Renewable, clean energy: the petroleum footprint - wind farms under analysis

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Keywords: wind turbines; wind farms; petroleum footprint; energy balance; net energy; environmental issues; renewable energy; clean energy; wind energy; wind power; fossil fuel consumption; oil consumption; emissions; oil footprint.

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Renewable, clean energy: the petroleum footprint – wind farms under analysis

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1 Introduction

Basically, this work deals with the generation of clean and sustainable renewable energy analysed in a broad sense. As the generation of energy to replace or substitute fossil fuels is usually sought, the first objective is to calculate or estimate a number representing the net energy gain in clean energy. In other words, how much fossil fuel is really saved, considering that the latter will inevitably be consumed, to a greater or lesser extent, at some stage of the construction, installation or operation process of renewable energy?

We consider this is not just an academic exercise. It should be an unavoidable task for all those who are involved in adopting alternative energies. This is a world where energy demand is growing exponentially and fossil fuels – beyond any other consideration, become critically scarce. Some people think that at the current rate of consumption growth, reservoirs known and those still to be discovered will become exhausted (world peak oil) (EIA, 2004; EIA, 2012). Others think that the great crisis will occur much earlier, when demand cannot simply be satisfied. Many agree that this will happen at an indefinite time close to the end of the XXI century. The consumption rate is set both by the industrialised countries (USA, Europe) and emerging economies such as those of China, India and other Asian countries, with a very low-level of per capita consumption compared with the world mean and accelerated growth trends.

In this context, it is vital to have a proper estimate of the effective energy gain and the power required to be installed. This is not only due to the necessary seriousness and consistency of projects, but also to the world situation which does not allow room for the choice of energy-inefficient developments.

The need and convenience of supplying all small cities, towns and rural areas, away from any mains supply or pipelines with any renewable energy is not under discussion. We mean massive substitution – with renewable energy of fossil fuels and nuclear generation, producing millions of MWh and m^3 of biofuel annually.

It is also necessary to consider supplies, emissions and collateral damage which are disregarded or hardly taken into account when selecting alternative energies. Besides, the issues of competition for cultivable land, consumption of fresh water, global pollution in the form of Greenhouse Gas (GHG) and local or regional pollution at the atmospheric level and in water bodies, the damage to people, fauna and flora, are all aspects that can no longer be overlooked. They are not the immediate aim of this work, but they cannot be omitted in the discussion of results or conclusions, since they are part of the problem and of the international agenda.

Referring to GHG emissions (CO_2) produced by the burning of fossil fuels mentioned above as ‘carbon footprint’ is common in the literature on Climate Change and Global Warming. Similarly, for each process or product, a ‘fresh water footprint’ or a ‘contaminant footprint’ can be defined. As in this work the predominant issue is the energy problem, the concept of ‘petroleum or oil footprint’ and not ‘carbon footprint’ is used to summarise the consumption of all energy consumed in the production of a given product, in this case in the generation of renewable energy. After all, there is no doubt nowadays that in our global society, *petroleum* is the name of energy. Likewise, it is not striking that the efficiency of renewable energy is measured by the oil savings it generates.

Finally, this study sets wind energy as an example of the entire alternative renewable energies for two reasons: First, it is the simplest case to be technically described. Second, it is the most developed renewable energy, which is expanding strongly, especially in

Europe. It is worth mentioning regarding the German government public decision, even when the incidents of 2010 in Fukushima (Japan) were still in progress, to replace much of the country nuclear generation by wind farms in the short and medium term.

2 Methodological framework to assess renewable energies

2.1 Turbines and wind farms

Modern wind turbines (see Figure 1) are enormous pieces of high technology, prepared to operate continuously (not without periodic maintenance and repair) for approximately 20 years, connected to large power networks (BERR, 2007; Kentish, 2011; Vestas, 2011; DECC, 2012; Siemens, 2012).

Figure 1 Offshore wind turbine (see online version for colours)

Source: Phault (Fotopedia)

Each one consists basically of a *nacelle* (see Figure 2) that contains a generator of 2.0 MW and up to 6.0 MW nominal (Rated) power, a main shaft, a rotor hub, a gearbox and a three-blade propeller of variable positions. They also have hydraulic and electronic systems for automatic operation and remote communication.

The *nacelle* is mounted on a steel tower 60–120 m high, with enough room to house wiring, emergency stairs and an elevator inside it. A concrete (cement, gravel, sand and steel) or steel foundation is required to support the full weight of the structure, wind load and waves (occasionally) in the case of generators assembled offshore.

When installed in groups (wind farms) (see Figure 3), it takes approximately 6–10 ha per turbine, so as not to generate interference or cause accidents affecting others (US EPA, 2010). In Europe, the lack of land has encouraged the proliferation of offshore farms, approximately 10–20 km from the coast. Their location and distance also ease the serious noise problem they pose. Each farm requires its internal network and wiring connection to the regional network, one or more converters, synchronisers and computerised systems to manage the link between both networks.

Figure 2 Wind turbine Nacelle (see online version for colours)

Source: Siemens UK (Siemens, 2012)

Figure 3 Offshore wind farm (see online version for colours)

Source: Siemens (2012)

2.2 General scheme to be used on the assessment

To perform a rigorous evaluation of each renewable energy project (wind farm), it is essential to perform a systematic and systemic study, covering numerous stages. During the first stage, the effective energy that the farm has to produce to feed the regional network has to be adopted. The nominal power and type of each turbine should also be selected and adopted, which will allow calculating the required installed capacity and number of turbines that constitute the farm.

At the second stage, an additional assessment of the resources needed to build, transport, install and maintain the facility in operation has to be done. Also, the energy required at the end of the useful life of the farm, for the necessary steps of disassembly, transport and setting the farm in the conditions required by the norms have to be assessed. This leads to an inventory of materials and well-defined operations.

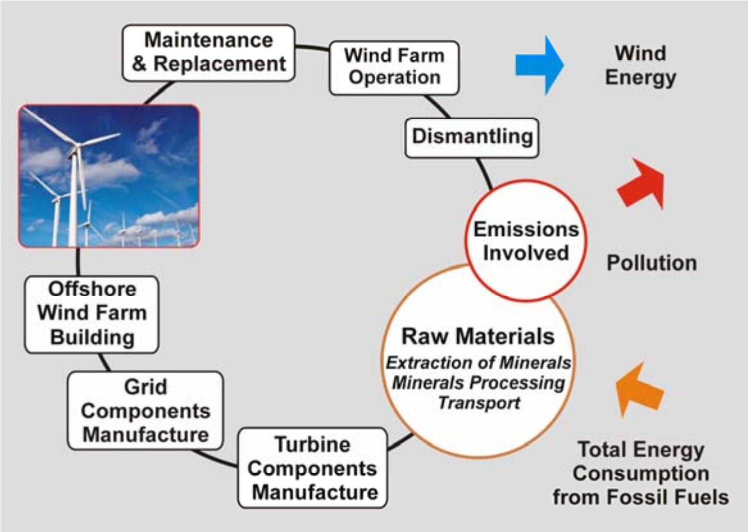
At the third stage, calculation and integration of all the fossil fuel (energy) consumed in each and every stage and operations previously surveyed, compared with the energy determined to be supplied to the regional network, as originally adopted, should be made.

At subsequent stages a survey should be conducted and quantification should be done on the general emissions and damage caused, both on obtaining and processing of the materials required by farm, and those necessary for construction, operation and disassembling. The steel, aluminium, polymers and cement industries among others are involved here. Damage to people, fauna and flora, emissions of GHG, local and regional non-GHG pollution and pollution generated by liquid effluents should be considered. We are aware of the importance of including carbon footprint in any assessment, but we do not consider it appropriate to limit emissions to the GHG.

Another important aspect that should not be overlooked is the appropriation by the industry and farming of fresh water in all the processes for the production of renewable energy. As in the case of personal or environmental damage, the use of a scarce social good (in a great extent of the planet) should be part of the qualification and evaluation procedure of any project.

A simplified view of the General Scheme is shown in Figure 4. To reduce the extension of the text and given the complexity of every stage, only the first three are discussed. However, all of them are likely to be demanded in an actual project of medium-large scale of a global or regional impact.

Figure 4 General scheme (simplified view) (see online version for colours)

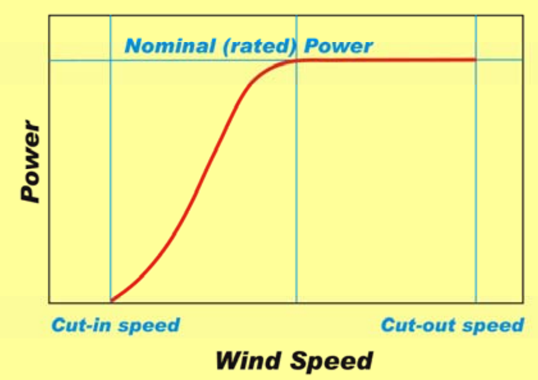


3 Calculations: an approach to the net energy of wind farms

3.1 Required installed capacity and number of turbines

The plan is to feed a national network (grid) with one or more wind farms supplying together 620,000 MWh/year or about 70 MW of effective power. This is the equivalent to the electricity needed by approximately 124,000 homes in Europe (5000 kWh annual consumption household segment) (Eurostat, 2012). Three-MW nominal power turbines are adopted. What is the installed wind farm capacity needed? How many 3 MW turbines are required? To answer these questions, the values of two basic factors have to be calculated: the first one, common in power plants is usually known as Availability Factor, and it is not always taken into account or calculated in the literature. The second one is the Capacity Factor, Power Factor or Wind Load Factor and emerges from the wind speed-power curve delivered by the equipment as determined by the manufacturers (sales power curve) (see Figure 5).

Figure 5 Wind turbine power curve (see online version for colours)



The nominal power is a feature of turbines and it is also certified by the manufacturer. It indicates how much power the equipment effectively delivers when wind speed is the nominal wind speed, practically the maximum power allowed (see Figure 5). See also the curves in the references (Vestas, 2011; Siemens, 2012).

The Availability Factor is the fraction of the total available time during which the equipment or the farm is actually producing electricity. It depends mainly on the winds in the area of installation and to a lesser extent on the behaviour of the equipment. In many geographical locations, the wind blows from 8% to 15% of the time with a speed below the minimum required for the turbine to operate (cut-in wind speed). On the other hand, 5–10% of the time, the wind reaches a speed exceeding the maximum permitted for operation (cut-off wind speed). With a wind speed above the cut-off speed, the safety systems stop the generation of electricity and block the blades to prevent damage. This percentage above cut-off speed is reasonable and justifiable, considering that the location sites are selected prioritising wind speed and persistence. In short, this factor describes the statistical behaviour of the geographic location and the actual operating time of the generator, considering downtime due to wind speed below the minimum or above maximum speed. An Availability Factor = 0.80–0.85 is considered to be a typical average value in the industry (Love, 2007).

The Capacity Factor is the number that best represents the average statistical behaviour of the geographical site and the equipment along the entire range of operating speeds. Values of 0.28–0.33 are considered normal, or in other words, the effective average power generated by the operating equipment is only 28–33% of the Nominal Power.

From the product of both factors we estimate that only about 24% of the Nominal Power is effectively used. Some works take 0.33 as a single value, and up to 0.45 (near the theoretical limit). In all cases they omit considering or estimate an Availability Factor (Weinzettel et al., 2009; Davidsson, 2011).

It can be corroborated that the mean value of 24% adopted here is conservative and realistic enough, considering the effectively generated power/nominal installed power ratio for several regions of Europe. The average ratio for 2010 in England (UK) does not exceed 24% (between 15% and 28% depending on the geographic location), 15% in Germany, 19% in France and 24% in Spain (DECC, 2012; Wikipedia, 2012). These numbers release us from considering other factors of a far lower incidence, such as maintenance problems, network synchronisation and others.

The answers to the questions raised above are answered by simple calculations, as summarised in Table 1, which shows that the total nominal installed power of the farm must be of 292 MW, with 97 turbines of 3 MW each.

Table 1 Nominal installed power and number of turbines

Effective energy supply to grid	*MWh/year*	*620,000*
Effectively generated power	MW	70
Nominal power of the turbine	MW	3
Availability factor		0.8
Capacity factor		0.3
Number of turbines		97
Nominal installed power	MW	292

The low effectively generated power/nominal installed power ratio is not just a problem of wind energy. It involves all systems relying on periodic natural resources. Such ratio for wind turbines accounts for 24%, and it scarcely amounts to 5% for photovoltaic cells. They are useful for only 8–10 hours a day, with a conversion efficiency of radiation-electricity not much higher than 15%. There is a classical problem with the manufacturing of ethanol, biodiesel and other biofuels. Their raw material can only be produced over a few months a year and collected as seasonal crops. The fact that these raw materials or their derivatives can be stored and kept available for manufacturing throughout the year is an operational advantage and not an energy bonus, since it does not mean more annual production. Therefore, there is nothing strange about seeking to widen the possible sources of raw material for the same final product.

3.2 Raw materials needed to install an offshore wind farm

The range, type and quantity of materials required to produce a wind turbine need no further explanation on the significant energy consumption needed to build an entire farm. Steel, copper, aluminium and cement are all energy-intensive products that are to be highlighted. According to manufacturers, the weight of a 3.0 MW turbine including underwater foundations is about 483 tonne (Vattenfall, 2010; Vestas, 2011), making a total of materials of 97 turbines of 46,852 tonne for a farm. The detail of materials is shown in Table 2 (Love, 2007; Riposo, 2008; ITS, 2009; Vattenfall, 2010; USGS, 2011).

Table 2 Offshore wind farm raw material

Raw materials	*% of total*	*Turbine*	*W. Farm*
		Tonne	*Tonne*
Steel	89.1%	431	41,761
Fibreglass/epoxy	7.2%	35	3373
Copper	1.6%	8	750
Cement	0.4%	2	187
Sand and stone	0.9%	4	406
Aluminium	0.8%	4	375
Total	100.0%	483	46,852

Notes: 97 turbines, 3.0 MW and 483 tonne each.

3.3 Energy consumption: raw material

The basic raw materials which appear in Table 2 account for most of the energy consumption within the components of a turbine or farm, so we have taken special care to determine a reasonably reliable value. It is not easy to adopt a single value to determine the energy consumption of each material. Regardless the variability of technologies and processes used in production, some available data report on the 'gross value' which includes energy losses due to equipment yield, electric transportation, material movement and others. Other data do not specify clearly the stages included. Almost all values represent the consumption 'in factory', i.e. no transportation to the turbine production unit is included. Water consumption for the process deserves a special comment. On most lists of energy expenditure or cost, fresh water appears to be as free as atmospheric oxygen. In many cases, the cost of pumping and treating process water is not even included. These missing factors create some uncertainty, which has forced us to always take the most conservative values.

Another aspect that should be considered is the lack of differentiation between primary and recycled products. As a criterion – not always respected – the value of the original production (virgin or primary production) must be selected regardless of the recycled material of a lower cost or mixtures with one another, a situation that occurs in almost all materials, except for cement. Recycling is a powerful economic and ecological tool, but it should not be considered when analysing the energy consumption in the processing of any product.

Accepting the uncertainties and adopting conservative numbers, a set of reference values for the five most relevant materials has been obtained. In two cases (copper and cement), the literature did not include the energy required in the mining process or transport of minerals to the next productive stage, therefore its correction was decided.

- *Steel:* Total energy: 32.0 GJ/tonne (MATS324, 2012). A second piece of information, which excludes mining and transportation, is 24.4 GJ/tonne (US EPA, 2010). The difference is 7.4 GJ/tonne.

- *Fibreglass/Epoxy:* The best reference is 54.7 GJ/tonne (MATS324, 2012) of total energy. A second piece of information that does not include extraction and transportation shows 50.0 GJ/tonne (Subic et al., 2009). Difference: 4.7 GJ/tonne.
- *Aluminium:* The best values of total energy are 185.0 GJ/tonne (MATS324, 2012) and 218.7 GJ/tonne (ITP, 2007). We adopt the mean of the two, about 202.0 GJ/tonne.
- *Copper:* The best value is 142.5 GJ/tonne (US EPA, 2005). It does not include mining or product transportation. We added 6 GJ/tonne to cover these two stages, following the trend of other authors (Li and Chen, 2009; Weinzettel et al., 2009; Davidsson, 2011) Final value adopted: 148.5 GJ/tonne.
- *Cement:* The selected value is 4.9 GJ/tonne (Jacott et al., 2003). In the case of copper we added 2.5 GJ/tonne. Final value adopted: 7.4 GJ/tonne.

Table 3 summarises the criteria stated above and the total energy consumption of relevant material for the whole farm, also using the data in Table 2. All units have been converted to MWh (megawatt hours) or MWh/tonne for the purpose of subsequent calculations. The resulting total energy for these five materials is 475.322 MWh, in the order of the global data found.

Table 3 Energy consumption: raw materials

Raw materials (1)	*Wind farm, MWh*	*MWh/tonne*
Steel	371,673	8.9
Fibreglass/epoxy	51,270	15.2
Copper	30,959	41.3
Cement	394	2.1
Aluminium	21,027	56.1
Total	475,322	
Replaced component (as raw materials)	28,519	
Grand total, five critical raw materials	503,841	

Note: (1) In agreement with the figures of Table 2.

Considering that over 20 years of useful life, at least 6% of the material must be replaced (bearings, blades and even whole towers), the grand total of energy consumed by these five critical materials is 503,841 MWh.

3.4 Energy consumption: other stages to consider

The production of raw material is only the first of several stages ‘demanding energy’ in the life of wind farms. We could repeat the methodology of the first stage for all stages, in a process that is long and difficult to develop and describe. As there are previous works by various authors (Davidsson, 2011), we will rely on them to calculate the remaining stages. The summary appears in Table 4.

- Manufacture of components of each turbine (generator, propellers, towers, parts of foundations and others). Estimates indicate that this stage consumes about 19% of the total energy.

- Manufacture of components required for the connection to the regional network (cables, transformers, electronics safety and others), 11% of the total energy. This value depends on the proximity of the site to the network.
- Transport of all components to the installation site of the farm. Following the references, a relative energy consumption of 8.4% is adopted, but not without highlighting that the figure does not bear generalisation: It is not the same to produce high-tech components (excluding towers and foundations) in Germany and transport them to the North Sea, as to install them in North Africa, Peru or Patagonia.
- Installation on site: 2% with the same remarks as above. Crane ships are required, available in just a few places of the world.
- Operation and maintenance: 9.6%. It includes the circulation of personnel, spare parts and supplies, in addition to the consumption of lubricating and hydraulic oils, and occasionally the use of crane ships.
- Dismantling: 1.5%. At the end of the useful life, it is necessary to remove all remaining material and turbines, including the remains on the seabed. This stage is not only set by the rules, but it is also necessary to recover money from the sale of materials that are not in use.

Table 4 Wind farm, total energy consumption

Stage	*Consumption, MWh*	*% of total*
Critical raw materials	503,841	48.5
Turbine components manufacture	197,381	19.0
Grid components manufacture	114,273	11.0
Transport of components to building site	87,263	8.4
Offshore building	20,777	2.0
Operation and maintenance	99,729	9.6
Dismantling (at the end of useful life)	15,583	1.5
Wind farm energy consumptions, grand total	1,038,848	100.0

Our concluding results are shown in Table 4. The total value of energy consumption required to build and operate the wind farm for 20 years is 1,038,848 MWh. For all the stated above, it is not an exact figure and not in the least applicable to generalisations. Its greatest value is that it gives us a strong basis to answer the main questions generated by this work, with the support of knowing that the right criteria and values were applied. Furthermore, at worst they will result in errors by default and not by excess.

4 Final energy balance: petroleum footprint

As discussed in Section 3.1, the farm was designed to generate an effective energy of 620,000 MWh/year for 20 years of useful life. This represents a total generation of 12,400,000 MWh. Considering the amount of energy required to assemble and operate the farm (Section 3.4), the consumption/generation ratio is only 8.4%, perhaps 10% if we include all the omissions discussed throughout this work. In any case, it is obvious that the net energy generated by the wind farm is largely positive.

However, it should be noted that petroleum footprint is very strong and their presence cannot be hidden, even in wind energy production with the highest technology available to date. 1,038,848 MWh represent 20 months of the total generation of the farm, used exclusively to satisfy the energy consumption that allowed building and maintaining it in operation for 20 years. If we convert that energy into liquid fuel, we can also express it as 89.000 tonne of diesel or slightly over 90,000 tonne of crude.

Neither 8.4% of the energy generated in 20 years nor 20 months over a total of 240 or 90,000 tonne of crude are small figures and should not be minimised. It should be a warning to review all technologies involved and obtain substantial improvements in energy efficiency with which wind energy is produced today.

Still in the field of energy, other challenging questions promptly arise: Will technological improvements be sufficient to justify the use of other renewable energies? Given the necessary industrial facilities and the level of consumption of liquid fuels in land management and transportation, is it worth the effort to develop and put into production new technologies to produce biofuels massively?

5 Man does not live by oil alone

This section is intended to recall that the energy balance is, in this hour of the planet, just one of the important aspects to consider. To evaluate the efficiency of a system of generation of 'clean and renewable energy' it is no longer possible to avoid the issues of water consumption, pollution and 'unavoidable unintentional damage' to people and nature.

In simplistic terms, emulating a risk analyst of an insurance company, we could quantify pollution and damage assigning it a cost and translating it into MWh or oil tonne. In fact, very few environmental variables are always calculated and incorporated into large industrial projects: Royalties for the use of water (very rarely), also the cost of treating liquid and atmospheric emissions, but without taking a single step beyond 'what rules state'. How is damage to humans and our habitat really quantified? What will be the price of the next disaster generated by climatic change? Does anyone seriously think that the negotiation and trading of emissions among the signatory parties of the Kyoto Protocol will change anything in the future?

Demarcation lines of all the 'applicable rules' are vague and flexible as well. They have been drawn mainly by governments to encourage investment and support 'sustainable development', in the first place. The defence of health and quality of life of the population, as well as the integrity of natural life are subordinated to economic development, as quoted from the preliminary document of the United Nations Framework Convention on Climate Change (UNFCCC) 1992. The reluctance of the USA to follow the entire common plan to reduce GHG emissions and the defection of Canada in 2011 are corroborations exempting us of any additional comments.

We grew up hearing people say that the environment would improve when technological progress allowed cleaner production. No one can deny the extraordinary technological advances of the last fifty years, but the world has not improved to the same extent, because we continue producing to accumulate, not to live better.

Many optimists think that the predictions of imminent and ominous energy crisis will fail if there is a scientific technological ‘miracle’ that gives us control over energy from atoms, via nuclear fusion or by the emergence of technologies and sources inexistent or unknown today. Unfortunately, there is absolutely no hint of a technological miracle in this century, or even in the next one.

What shall we do until the dilemma is solved? The most basic survival logic would indicate that we must set new trends, reasonably moderate energy consumption and exploitation of natural resources; reduce the risk of climate change and global warming. It is not the point to slowdown the economic growth, but producing differently, eliminating inefficient and superfluous production.

Science and techniques required to initiate numerous changes are already available, but they are not applied due to lack of planning, agreement or resistance on the part of the groups allegedly harmed. An example that requires no demonstration is the replacement of the current car fleet by hybrid vehicles, with electric motor as the only source of torque, acceleration and speed. The hybrids produced today are luxuries for the few, in number not enough to seriously improve the trend. In parallel, we should work hard to develop new technologies in all fields, without expecting miracles, selecting only those that really make the difference.

6 Conclusions

A methodology for the evaluation of clean renewable energy projects, applied to the estimation of large wind farms has been submitted and developed. Even though this work has been restricted to energy aspects due to practical obvious reasons, we envision methodology as necessarily systematic and systemic, applied to real and concrete projects.

It is evident that wind energy is shown as one of the cleanest promising alternatives. Along with solar power, they may be today the two renewable sources technologically less dependent on oil and other fossil fuels.

However, their level of energy efficiency is not as high as it might be expected. Very conservative estimates indicate that 8 to 9% of the total energy produced in the 20 years of useful life is necessary to cover the oil consumed to build and maintain it in operation throughout this period. Stricter estimates are likely to increase this percentage to 10–12%.

In any case, it seems essential to review and improve in the future all the currently sustaining technology. To a lesser extent, improving the operating performance of turbines, but fundamentally, changing the materials and construction techniques used today, all highly dependent on fossil fuels, is vital.

How much would the overall efficiency of wind power decrease by incorporating into the assessment all emissions and unwanted damage, both at the operational stage as well as at the stages consuming oil? This is the question still to be answered. It is an issue which is insinuated, but not disclosed by this or other previous work, necessarily applicable to all the alternatives of renewable energy.

In addition, it seems inevitable to conclude that the search for clean renewable energy is not enough. We must reorient – by means of education and consensus – the way this global society consumes, produces and manages its natural resources. If this is not done, the future will become unpredictable.

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