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A global renewable mix with proven technologies and common materials

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ABSTRACT

A global alternative mix to fossil fuels is proposed, based on proven renewable energy technologies that do not use scarce materials. The mix consists of a combination of onshore and offshore wind turbines, concentrating solar power stations, hydroelectricity and wave power devices attached to the offshore turbines. Solar photovoltaic power could contribute to the mix if its dependence on scarce materials is solved. The most adequate deployment areas for the power stations are studied, as well as the required space. Material requirements are studied for the generation, power transport and for some future transport systems. The order of magnitude of copper, aluminium, neodymium, lithium, nickel, zinc and platinum that may be required for the proposed solution is obtained and compared with available reserves. Overall, the proposed global alternative to fossil fuels seems technically feasible. However, lithium, nickel and platinum could become limiting materials for future vehicles fleet if no global recycling systems were implemented and rechargeable zinc–air batteries would not be developed; 60% of the current copper reserves would have to be employed in the implementation of the proposed solution. Altogether, they may become a long-term physical constraint, preventing the continuation of the usual exponential growth of energy consumption.

1. Introduction

According to the Association for the Study of Peak Oil and Gas (ASPO), worldwide peak production of crude oil (Peak Oil) is expected to occur during the early decades of the 21st Century (Bardi, 2009; Aleklett et al., 2010). Other fossil fuels, such as gas and coal, are also expected to peak around this date (Mohr, 2010; Energy Watch Group, 2009; Patzek and Croft, 2010). Therefore, an increasing excess of oil demand relative to the available oil production is likely to happen during the next decade (JOE, 2010; Roberts, 2010; Fogatt, 2010).

Given the strong dependence of current technologically advanced economies on oil, Peak Oil may be a distress for entire economic sectors (Hamilton, 2009) if no alternative primary energy is made available during the next decades to take the place of fossil fuels (Hirsch et al., 2005). In a recent report, Heinberg (2009) defined four conditions that a future primary energy source substitute should satisfy:

i. must be able to provide a substantial amount of energy—perhaps a quarter of all the energy currently used nationally or globally;
ii. must have an Energy Return on Energy Investment (EROEI) of 10:1 or above (see Appendix A);
iii. cannot have unacceptable environmental (including climate), social or geopolitical impacts;
iv. must be renewable.

Moreover, as discussed in this manuscript, an additional requirement must be also considered:

v. Must not depend on the exploitation and use of scarce materials.

The potential primary power sources that remain after this first screening process are wind and concentrating solar thermal (CSP) devices. Besides, the engineering of both technologies is well known and understood and do not actually depend on rare earth elements (REE) and/or scarce materials. However, a solution based on wind turbines and solar would be possible only if enough reserves of the required (common) materials are available.

Nowadays, two theories about economical resource exploitation are usually invoked when investigating the future availability of any scarce material: *resource-based* and *reserve-based*. According to the first approach, all mineral resources are abundant enough, and new reserves may be made systematically available as the price of that resource increases enough. It lies on the belief that a high price of any material will always mobilise large amounts of capital and technological inputs to develop it or to find a substitute resource (Barnett and Morse, 1963). The drawbacks of such hypothesis are two: (i) while rising investments increase the probability of finding

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new technological innovations to develop the resource, the actual outcome is not granted at all, and the production is not increased to the desired rates and (ii) high mobilisation of capital in response to price may be expected in a scenario of rising Gross Domestic Product (GDP) provided that the prices of other basic products do not rise in larger proportion. Given the observed strong dependence between GDP and useful energy (Kümmel, 1982; Warr and Ayres, 2006; Warr et al., 2010) a scenario of rising GDP cannot be given for granted after the peak of fossil fuels. Because of these drawbacks, the approach followed in this work is based on the more conservative *reserve-based* one (Gross and Veendorp, 1990), which assumes that reserves will not be expanded any longer. Both GDP and *response to price* are plausibly rising functions of the socially available net energy (Hall et al., 2008), and this energy (E_u) is a non-linear decreasing function of EROEI (see Appendix A). The EROEI of fossil fuels has been decreasing in the last century (100:1–20:1 in the case of US oil production according to Heinberg, 2009), and it is expected to reach critical values under 10:1 soon after the peak of fossil fuels. For these critical EROEIs, the economical mobilisation to produce even basic consumption products will decrease because most of the energy would be consumed just to keep energy production, and the stock of capital to produce scarce materials will decrease plausibly in much larger proportion.

Jacobson and Delucchi (2011) and Delucchi and Jacobson (2011) propose a feasible future energy production mix similar to that of Heinberg (2009). They suggest that 51% of the 2030 demand could be provided by 5 MW wind turbines, 40% provided by photovoltaic (PV) and concentrating solar plants, and the remaining 9% provided by hydroelectric stations. Pacala and Socolow (2004) proposed a solution with a mix of 15 "wedges" or strategies available with the current technology. Two of these wedges were to increase 100 times the current capacity of installed wind turbines and 700 times the current capacity of solar PV power. Sovacool and Watts (2009) have shown that a completely renewable power sector is technically feasible in USA, New Zealand and probably in the world, and this renewable power would be based on wind, solar PV, CSP, geothermal, hydroelectric and biomass.

In any case, the full substitution of the present fossil-fuel based energy model by a mix of renewable energies would inevitably lead to the almost complete electrification of society. Thus, the resources necessary for energy production and those required for the electrification of society must be taken into account.

The main question asked in this work is: are worldwide estimated reserves, as well as production rates, able to sustain both the transition to a proposed renewable energy substitution mix and the electrification of society?

The plan of this manuscript is the following. In Section 2 a renewable mix of hydroelectric, wind, solar and wave technologies is proposed. Section 3 discusses the material requirements for both the construction of the proposed mix and the electrification of society, focusing on the electrification of the transportation of both people and cargo. Finally, in Section 4 a final discussion is presented.

2. Global solution based on wind turbines, concentrating solar thermal and hydroelectricity

Jacobson and Delucchi (2009) assume a global consumption, for 2030, equivalent to 16.9 TW of mean power predicted by the US Energy Information Administration (EIA, 2009). However, according to these authors, the demand should be a fraction of this figure because: (i) a completely electrified economy saves energy, since electricity is a more efficient way to produce movement than combustion is; (ii) energy requirements of petroleum refining can be subtracted and (iii) some modest energy savings can be implemented in domestic consumption. All combined, these authors assume that only 11.5 TW (the 68% of the total mean power) should be produced by the renewable mix to satisfy the 2030 demand of an electrified society. This is close to the 2010 production of 12.5 TW. Current electric generation is only 2 TW, so a six-fold increase is required.

2.1. Wind, water and solar proven technologies

Windmills of 3–5 MW are being currently built and installed; this is a proven technology in expansion. The EROEI of wind turbines has been estimated in the range 15:1–40:1 (Kubiszewski and Cleveland, 2007). The capacity factor (CF, i.e. the ratio of the power actually produced to the theoretical maximum) of commercial turbines has improved over time, from 0.22 for units built before 1998, to 0.30 for units in 2000–2001, and 0.36 for those operating after 2004–2005 (US DOE, 2008, p. 27).

The EROEI of CSP stations is close to 20:1 (Vant-Hull, 1985). Parabolic trough stations are more extended and proven CSP technology. Even though the first parabolic trough station without heat storage had a CF of about 0.13–0.25, Andasol I, in Spain, has a CF of 0.40. In its 200 ha of surface, Andasol I is formed by a set of cylindrical-parabolic mirrors, using 14,000 t of steel, and includes two tanks containing 28,500 t of a mixture of 60% NO_3Na (sodium nitrate) and 40% NO_3K (potassium nitrate). These salts melt during the day, accumulating energy as latent heat, and release it at night. The station produces up to 50 MW during the day and 7.5 h of night and a mean energy of 21 MWyr. The heat losses from the tanks are estimated to be 2.7% per day (Solar Millennium AG, 2008). Alternatively, central power plants are also able to store energy in the form of heat with even more efficiency due to their higher operating temperature.

From now to 2030, plausible technology developments would permit colonising continental shelves up to 225 m depth with both founded and floating offshore windmills. In addition, two hybrid wind-wave systems could enhance the yield and power stability of offshore wind turbines: (i) attaching attenuator floaters at the base of windmills and (ii) deploying floating platforms with attenuators at the base and wind turbines above. An example of this technology is the Green Ocean Energy Ltd. prototype of 0.5 MW (see: http://www.greenoceanenergy.com/index.php/wave-treader). Another example of attenuators is the *Pelamis* floaters, from Ocean Power Delivery Ltd. (Drew et al., 2009), which generate 0.75 MW with a 120 m long device. An example of the second approach is the Floating Power Plant prototype (see: http://www.floatingpowerplant.com/), designed to produce 10 MW, 56% from waves and 44% from three windmills.

The three main advantages of hybrid installations are: increased energy return per square kilometre; reduction of maintenance costs of equipments and undersea transmission cables; and compensation of wind generation intermittency, as wind and waves are not necessarily correlated (with the exception of storms).

2.2. Proposed solution

The capacity factor of CSP stations with storage depends on latitude and insolation. Trieb (2006, see his Figs. 2–21) did show that a CSP station with 24 h storage may reach a CF of 0.9 at 25°26′N (El Kharga in Egypt), but it decreases to a value of about 0.4 at 40°N latitude (i.e., Madrid). Here, a value of 0.75 for CSP with storage built in sunny deserts with latitude under 30° is considered, and a CF of 0.4 for less sunny conditions (i.e., China, North America).

The cooling of steam circuits of parabolic troughs and tower stations requires water. In the case of Andasol 1, 870,000 m^3 of water is required per year, or 17,400 m^3/MW. In deserts, where water is scarce, Dish Stirling systems could be used instead. They use air instead of water and have a CF of 0.25 (NREL/SR, 2002). The surface required per MW is 4/5 of that required by parabolic troughs.

Both technologies need adequate geographical placements to minimise intermittency and maximise annual power production. Parabolic troughs or tower parks should be installed ideally in regions with: (i) high annual high insolation and (ii) access to water. Subtropical regions are rich in solar input but they are poor in water resources except for specific regions within mountain ranges and/or large river drainage basins.

Another adequate placement for CSP with storage is close to the sunny desert shorelines because a fraction of the heat released by the thermodynamic cycle could be used for desalination, and a fraction of this water could be used for cooling and mirror cleaning (Knies, 2006). According to him, 65% of the energy gathered by the plant is released as heat. If this heat were to be used for desalination only 15% would be lost and 50% would be used to separate the salt. In this way, 40 million cubic metres of potable water could be obtained per TWh produced. If 426 TWh were to be produced in the Sahara shoreline with 65 TW of installed capacity (see Appendix D, Table D.2) they would allow desalination of 17×10^9 m^3 of water. Moreover, as 1000 t of fresh water is needed to produce 1 t of wheat in a desert area (Saudi Arabian Monetary Agency, 2007), 17 million tons of wheat could be produced, i.e. 6.4 times the wheat production of Saudi Arabia in 2005.

Nocturnal electric demand in developed areas can be especially large during summer because of the high air conditioning consumption. For instance, the daily cycle of electric consumption in California in the 2005 summer had a maximum of over 50,000 MW and a minimum of 25,000 MW (California Independent System Operator, 2010; Hoste et al., 2008). As a result, a 30% of the total consumption was demanded during nocturnal hours. This figure can be used as an upper bound to the nocturnal fraction in any day of the year.

Table 1
Energy production mix proposed.

Type	Power fraction (%)	Capacity factor	Rated power (MW)	Units
Wind turbines	47.5–51	0.31	4.66–5	3,837,000
Stirling plants/air cooled CSP	28	0.25	300	50,460
Parabolic stations, 12 h storage	12	0.4–0.75	300	9800
Hydroelectricity	9	0.88	1300	900
Attenuators	0–3.5	0.4	0.75	0–1,123,000

While Dish Stirling stations have several advantages over parabolic troughs, they do not allow energy storing to supply nocturnal demand. A possible global solution could employ a mix of both technologies: parabolic troughs and central towers (30% of the installed solar capacity) to satisfy the energy storage needs and to cushion punctual demand peaks; and Dish Stirling stations (the remaining 70%) to meet the diurnal demand. The precise fraction of nocturnal demand should be estimated for every world zone. The water dependence of such 30% of stations could be eased if air cooling were to be used. According to the US DOE Report to Congress (2007), air cooling saves 90% of water requirements, although it reduces the plant power performance. This penalty is not insurmountable: 4.6% in trough plants and 1.3% in towers, with an electricity cost penalty of 7–9% in troughs due to the use of electric fans for cooling. Hybrid wet/dry cooling reduces water consumption by 50% with only 1% drop in annual electric output, or 85% with only a 3% drop in output. In this case, cost would increase by 5% compared to a water cooled plant. Some combination of these kinds of alternatives could be appropriate in areas where no water is available.

As a summary, Table 1 displays the energy production mix proposed here. It follows closely that proposed by Jacobson and Delucchi (2011) but with CSP substituted for PV power.

Fig. 1 shows the annual mean of near surface wind speed, along with the continental shelf where offshore wind turbines could be built. Places with mean winds above 6.5 m/s at 50 m are normally considered adequate. Most favourable areas are those where the blue or dark blue tones coincide with continents or shelves. These areas coincide also with regions with the highest, larger than 40 kW/m, wave energy (Krogstad and Barstow, 1999).

If a 0.75 MW wave device were to be attached to half of the proposed 2,246,000 offshore windmills, and, if a CF of 0.4 is assumed, almost 0.8 TW could be generated from waves, which amounts to 3.5% of the power needed globally. This would permit the CSP contribution to be only 37.5%, or the wind contribution to be only 47.5% of the total (e.g. an equal number of turbines but with 4.66 MW instead of 5 MW). A similar contribution to the total demand could be obtained from PV power by installing

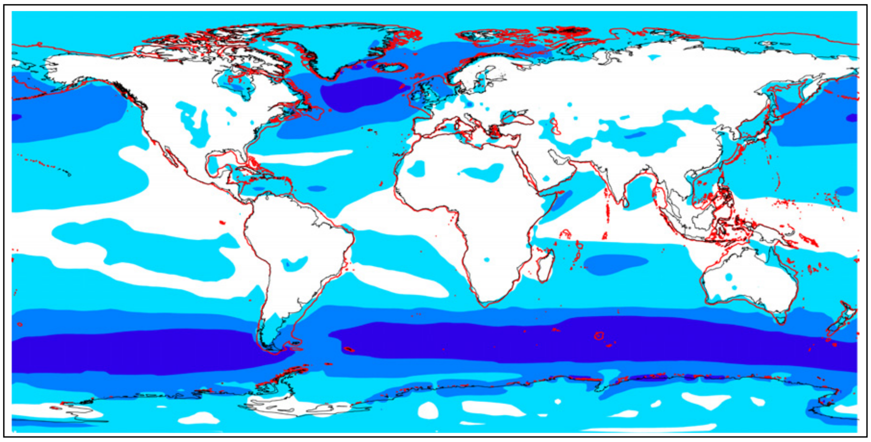

Fig. 1. Annual average of wind speed at 50 m above the surface of the Earth in m/s. Data downloaded from the NASA Surface Meteorology and Solar Energy site (SSE, http://eosweb.larc.nasa.gov/sse/, release 5.0). Light blue, blue and dark blue correspond to regions where the wind speeds are in the ranges 6–8 m/s, 8–10 m/s and > 10 m/s, respectively. The red line delineates the 200 m isobath, representing the continental shelf. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

about 994 million domestic panels around the world, although the main problems to be solved by PV systems before they may be scaled are commented in Appendix B.8. Jacobson and Delucchi (2011) propose a system with 1.7×10^9 roof PV systems, which do not require extra land for the facilities, reducing the cost associated with wiring a large-scale electric grid, while allowing the domestic use of the excess of heat produced at the panels. An additional TW could be also contributed by Ocean Thermal Conversion Energy if its problems with pipe stability and high cost are solved in the future (see Appendix B.6).

2.3. *Area constraints*

Fig. 2 shows several places in the subtropical regions of the world continents that satisfy the requirements commented in Section 2.1 (dots in the figure). There are eight locations that could be used to install parabolic troughs and tower plants (in grey) and another set (in blue) where Dish Stirling stations and CPS with air cooling could be installed. The area of the dots represents (multiplied by two for visibility purposes) the area demanded if all of them were to be concentrated in these 16 locations. These areas have been estimated using regional consumption weights, which represent the fraction of the total world consumption implied by a region, predicted by the IEA (2009, p. 76) for 2030 (Appendix D).

The large area required for the Eastern Asia demand contrasts with the relative scarcity of high-insolation deserts there. However, the area needed in Asia could be reduced by 50% if half of the consumed power were to be imported from the Australian deserts.

Denholm et al. (2009) have analysed the current US wind farms to obtain the footprint and total area affected by onshore wind farms construction. While the mean footprint is 0.3 ha/MW, the total area circling the wind farm depends on the arrangement of the windmills: it is 34 ± 22 ha/MW on average, but only 13–20 ha/MW if mills are arranged as clusters of ordered lines.

To have an estimation of the area affected by the proposed solution, the European region is taken as an example. The expected weight of Europe in the world consumption in 2030 is 0.14 (Table D.2). Assuming that 51% of it comes from wind and that 70% of this amount will be produced offshore, the total surface needed would be 89,079 km^2 if the arrangement is ordered (16.5 ha/MW).

With the current offshore technology, being used in the North Sea waters in Europe, the foundation of turbines must be placed no deeper than 30 m, while floating turbines can be placed at locations as deep as 220 m (Siemens inaugurated on September 8, 2009 a 120-m-tall, floating 2.3 MW *Hywind* turbine in the North Sea, the first operational deep-water floating large-capacity wind turbine). The part of the continental shelf within 0 and 225 m depth has been calculated using the geophysical $1'\times 1'$ map from the National Oceanic and Atmospheric Administration (GEODAS, 2010). The resulting area is about 2,574,000 km^2. Thus, the total area affected by the turbines would be 3.5% of the available shelf if windmills were placed in an ordered array.

If 30% of the total power is produced by onshore windmills, they will provoke a landscape impact that can be calculated using the parameters above. For a region such as the Iberian Peninsula, and assuming an energy demand of 260 GW, 7.5% of the territory would be affected by the presence of wind turbines. However, land-use impact of "spacing" area is expected to be smaller than the impact of the physical footprint.

2.4. *Intermittency constraints*

The unwelcome power variability associated with renewable sources may be mitigated by: (i) geographical interconnection (Zhou, 2009); (ii) use of hydroelectric power to smooth out supply (Czisch and Giebel, 2006); (iii) using reversible Electrical Vehicle (EV) recharging as grid storage (Kempton and Tomic, 2005); (iv) using other electric storage systems, as for example, water pumping, air compression, batteries, hydrogen production and storage and (v) using smart demand-response management and weather prediction to better match inflexible loads to the power supply (Delucchi and Jacobson, 2011).

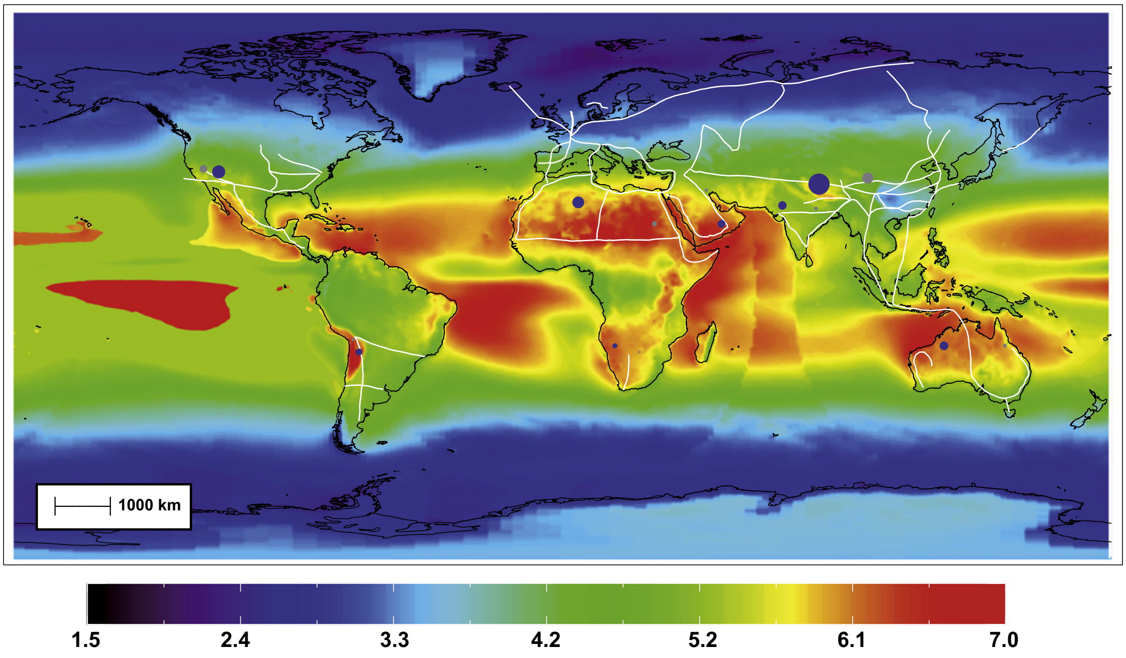

Fig. 2. Annual average (July 1983–June 2005) of incident insolation on a horizontal surface in kWh/m^2/day. Data downloaded from the NASA Surface Meteorology and Solar Energy site (SSE, http://eosweb.larc.nasa.gov/sse/, release 6.0). Grey and blue dots have twice the real areas occupied by the CSP stations to improve the readability of the figure (see text for details). White lines represent main distribution grid lines. The length scale corresponds to latitude 45°N. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

According to Czisch and Giebel (2006), the current monthly electricity consumption in the European Union (EU) could be entirely provided by wind with the proper geographical integration and hydroelectric storage. In their model, one-third of the rated capacities were assumed to lie within the EU, with the rest equally divided among Northern Russia, Western Siberia, Kazakhstan, Southern Morocco and Mauritania. The infrequent underproduction moments could be matched by using the current hydroelectric system in North Europe to prevent power shortages and, in overproduction periods, electricity surplus may be directed into pumping water back to the reservoir.

An encouraging proof of the power of this kind of grid integration was offered by the Spanish Electric Grid (Red Electrica Española, 2009) on 2009 November 8th during the night, when over 50% of the electricity production (with a peak of 53%) came from wind turbines and the electric system, instead of disconnecting the turbines, accepted all the wind power. The moderate variability was due to the large number of turbines (about 10,000, spread out through an area of about $1000 \times 1000\ \mathrm{km}^2$), a moderate international interconnection (10% of power) and 9.7% of hydroelectricity.

On the other hand, Kempton and Tomic (2005) have shown that vehicles to grid (V2G) systems, by themselves, could fill the gaps due to variable winds if half of the electricity was powered by wind and 3% of vehicles were used for storage.

Finally, Hoste et al. (2008) have shown how a mix of wind, solar and hydroelectric power could adapt to the seasonal and daily demand cycles in a region such as California. In their model, hydropower was the main buffer, and when production was over demand, the excess power was used to recharge EV fleet and to generate hydrogen for aviation and for the fuel cells system.

3. Materials availability

3.1. Steel and concrete

A solution based on CSP and wind turbines is possible only if enough reserves of steel, concrete and copper are available. The main components of concrete are sand, gravel and limestone, which are not scarce and easy to recycle and re-use. Steel reserves are estimated to be enough for 100–200 years at the current production rate (US Geological Survey, 2009, p. 81) and it is not expected to constrain the construction of 3.8 million turbines and 60,000 solar stations. The Vestas-V90 3 MW turbines weigh 132 t per MW installed. Taking this figure as adequate for large turbines and 180 t/MW as a typical steel consumption of CSP stations (the case for Andasol 1) 3800 million tonnes of materials (mainly steel) would have to be used to build the power stations. In 40 years, this would be equivalent to 95×10^6 t/yr, which is in the same order of magnitude as the car industry production (73×10^6 t/yr). In addition, a fraction of the steel could be recycled from a large number of current low-power turbines at the end of their useful life. End of life recycling rate (ELRR) of steel has been estimated to be 70–90% currently (UNEP, 2011, p. 30).

3.2. Nitrates

The supply of 12% of power demand with CSP with heat storage would require the use of large quantities of sodium and potassium nitrates. The nitrates mixture usually employed has a fusion enthalpy of 100 J/g (Laing et al., 2009). To supply 1.4 TW during 12 h of nocturnal demand 596.2×10^{14} J has to be stored, which requires 596.2 Mt of nitrates. The main reserve and only source of commercially exploited natural nitrates in the world is in Atacama, Chile, where 37 Mt of reserves have been reported (SQM, 2010, p. 5). The world production of sodium nitrate is about 1.43 Mt/yr. These figures show that the proposed solution would have to be based on synthetic production of nitrates, which may decrease the EROEI of the CSP with heat storage, given that a fraction of the CSP output would have to be employed in the synthesis.

To have a rough estimation of this reduction of EROEI, the materials and energy involved in the synthesis of ammonia (Haber process), and ammonia to nitric acid (Ostwald process) will be examined. In the first process, 0.46 t of natural gas and about 8.6×10^9 J of energy are needed to produce 1 t of ammonia (NH_4). In the second process, 0.405 t of NH_3 and 0.56×10^9 J are used to produce 1 t of nitric acid (HNO_3) or nitrates (Wang et al. 2003). Natural gas combustion produces 49×10^6 J/kg. Its EROEI is currently about 20 (Hall et al. 2009). With these parameters, about 4.49×10^9 J would be needed to produce 1 t of nitrate in the next years. Assuming that the station would produce energy for 30 years, the fraction of energy needed to the synthesis can be estimated to be 0.4% of the energy produced by the station. Therefore, by using the definition of EROEI (Appendix A), this parameter is expected to decrease from its value without synthesis (about 20) to 18.5. This implies a decrease in useful energy for the fraction of power to be supplied by heat accumulation, but it does not make the proposed solution unviable.

3.3. Neodymium

Windmill generators may be built using permanent or non-permanent magnets. In the first case, a 5 MW wind turbine may have a 2 t magnet, of which 12% of its mass is neodymium (Nd) and other REE (Kramer, 2010). The problem with Nd is not with reserves, which are large (about 8×10^6 t), but with its production rate of only 7000 t/yr in 2001 (Emsley, 2003, p. 268). Thus, if 3,780,000 windmills were to be built within 30 yr, the amount of Nd to be extracted would be 30,240 t/yr, which is more than four times the 2001 production rate.

On the other hand, China is presently the source of more than 95% of the world's supply of Nd and other rare earths. Chinese output of rare earth is expected to grow up to 170,000–185,000 t by 2015. Domestic Chinese consumption is expected to be 125,000. As the global demand will be 190,000–210,000 t in 2015, the gap between global supply and global demand will monotonously increase in the next decades (Kramer, 2010).

3.4. Copper (Cu) in power production

Wind farms use Cu in the wind turbine generators, in the low power conductor from the generator to the medium voltage transformer (MVT), in the earthing cables surrounding the tower, and in the earthing cables of the farm. These normally go with the underground Medium Voltage line from the MVT to the high voltage transformer (HVT) connecting the farm with the external grid. A fraction of copper is found also in alloys belonging to the tower structure, transformers and control systems.

Most of the currently used wind generators are three-stage gearbox Doubly Fed Induction Generators (DFIG). The Vestas-V90 wind turbine of 3 MW is an example of this kind of design. Appendix C shows the assumptions and parameters used to calculate the copper utilised by this model, which is taken as a reference.

The final result is 2.7 t/MW of copper for wind farms with standard windmills and 1.85 t/MW if the windmills have the LV/MV transformer in the nacelle. In this calculation we will assume that half of the future windmills will use the latter design.

The International Copper Association has estimated that globally 800 MW of energy produced by wind power and other non-conventional energies requires 1200 t of copper, that is, 2 t/MW (Mercurio de Calama, 2010). This estimation is close to the global figure estimated here for onshore wind farms.

In offshore wind farms the amount of required copper increases with the distance to the coast. The Borkum 2 offshore wind farm in Denmark uses 5800 t for a 400 MW connection to the grid of 200 km (ABB 2007), which implies 14.5 t/MW. The Horns wind farm, with a submarine connection of 21 km, uses a 630 mm^2 copper line with 70 kg/m (Christiansen et al., 2010, p. 3) to transmit 160 MW to the external grid. This is equivalent to 8.75 t/MW or 0.416 t/(MW km). Therefore, an adequate figure to calculate the Cu usage in offshore windmills is 10 t/MW. Copper consumption in CSP stations is assumed to be similar to that in onshore wind farms, i.e. 2 t/MW.

If it is assumed that solar production will be based on 70% of Stirling dishes or air refrigerated CSP stations and 30% of water refrigerated CSP with storage, and that 70% of future wind turbines will be offshore, the copper required for power generation is 147 Mt for wind turbines and 36 Mt for solar stations, making a total of 183 Mt.

3.5. *Copper in power transmission*

Now we calculate the copper needed to build high voltage lines between the regions of solar production and the regions of consumption. We assume that the solar production is concentrated close to the 16 dots shown in Fig. 2. Weights are given to these dots depending on the expected electric demand of the regions close to them, as showed in Appendix D, Table D.2.

According to Trieb (2006), the most efficient way to transport electricity to large distances is High Voltage Direct Current (HVDC) lines. Fig. 2 shows the main HVDC paths that the Global Green Grid Programme (Global Green Grid, 2010) has proposed to connect production with consumption regions worldwide and some additional paths that we have added to connect good regions of wind production.

Appendix D shows the assumptions and parameters used to calculate the power transmitted along the paths connecting production and consumption regions, the installed capacity at origin after taking into account transmission losses and the copper mass needed to build a simplified HVDC grid sketched in Fig. 2.

The conclusion is that the amount of Cu needed to implement the transmission of solar and wind power to the grid is estimated to be 38 Mt, to be added to the 183 Mt needed in the generation stations, which makes 221 Mt. Current global production of copper is 16 Mt/yr and economically exploitable global reserves are estimated at 550 Mt (US Geological Survey, 2009, p. 54). Therefore, 40% of the total reserves (the production of 14 yr) had to be invested in the construction of wind turbines, solar parks and HVDC lines. Of course copper recycling would reduce the pressure on mine reserves; it is however assumed that recycling will only marginally provide copper for the establishment of the new system because it is intended to add up to present uses, and so recycling would provide copper mainly for new appliances, vehicles, etc., substituting the older ones.

3.6. *Aluminium in power transmission*

The aluminium (Al) needed in the MV transmission in a mean wind farm can be estimated using 400 m/MW for the MV transmission (Appendix C). Typical wind farms analysed in Appendix C use 3×95 mm^2 Al cable for connection between turbines (which will be assumed to be 2/3 of total length) and 3×150 mm^2 Al cable to connect with the HVT (1/3 of the total length). With these assumptions, 0.37 t/MW is the amount of aluminium required.

The total Al needed to implement the transmission can be calculated using the mean lengths shown in Table D.1 and the tonnes of Al per km used in overhead lines (Table D.2). About 44.2 Mt would be used, to be added to 2.2 Mt used inside the wind farms, which makes a total of 46.4 Mt. Global aluminium reserves are 5.86×10^9 t, according to the US Geological Survey (2009, p. 28), and global annual production was 33.4 Mt/yr in 2006. Thus, less than 1% of the reserves had to be employed in the construction of the new HVDC lines, which is equivalent to the production of 1.4 yr.

3.7. *Copper in transport*

While hydrogen has been proposed as a storable energy carrier to supply fuel, comparable to oil and natural gas (mainly for transportation), renewable electricity transfer by hydrogen would force three quarters of the power generators to work exclusively for covering the energy losses of the hydrogen conversion chain, mainly in electrolysis, package, transport and fuel cell conversion steps (Trieb, 2006, p. 13). According to Ruth et al. (2009) water electrolysis from wind power followed by pipeline delivery is able to produce hydrogen at 7.16 2005\$/kg-H_2 (2005 dollars per kilogram of hydrogen) if electricity price was 0.082 \$/kWh. Assuming that a typical fuel cell consumes 0.06 kg-H_2/kWh (CellKraft, 2006), fuel cell production of electricity is 5.2 times more expensive than the direct use of wind electricity. Thus, the direct use of electricity by motor vehicles must be considered a cheaper, and more efficient, way to produce movement, and it should be considered the most promising option in future transport systems. The exception would be planes and other transports that are not able to take the energy from the electric grid and vehicles with specific requirements of autonomy and power.

If electricity is going to be the main energy carrier in transport a first step would have to be the complete electrification of the current world railways. Appendix E shows the parameters used to estimate the amount of Cu required for this. The conclusion is that the copper needed for this conversion is about 110,000 t.

Concerning vehicles, Appendix F details the assumptions and parameters used to calculate the copper that would be used if the current vehicles fleet were to be converted to EVs.

The number of motor vehicles in circulation in 2004 has been estimated by Walsh (2005). By extrapolating linearly the tendency observed between 1994 and 2004, the number of vehicles in 2011 can be estimated to be 584×10^6 cars (light vehicles), 240×10^6 commercial (heavy) vehicles and about 270×10^6 motorcycles. We will assume that a fleet of EV equivalent to this is built and that 10% of the EV is powered by fuel cells. By using the parameters shown in second line of Table 2 and in Appendix F, the copper used can be estimated to be 98 Mt.

Adding the power generation copper requirement (221 Mt) and the contributions coming from railways and electric trains (10.7) and electric cars (98), it is found that about 330 Mt of Cu would be required for the new economic system. This implies that 60% of the copper reserves would be used, which is equivalent to 21 yr of the current production.

Jensen (2007) has proposed a RUF Dual Mode Transport System that could organise a large fleet of EV allowing them to take power directly from the electric grid in interurban travels and reducing the battery size, which would be used only in local displacements. The global road network length has been estimated to be 102 million km (The World Factbook, 2010). Let us assume that such a system were to be built with two copper cables of 107 mm^2 for power distribution on 14% of world roads (in Spain this fraction corresponds to the interurban roads). The copper needed would be 54 million t, increasing the fraction of copper reserves used from 60 to 70%.

Table 2
Values used for the estimation of metals required by the transport system. Density refers to the mass of metal used per unit of power or per unit of energy stored in engine, battery or fuel-cell.

Metal	Density	Global mass (t)	Reserves[a](10^6 t)	Production (10^6 t/yr)[a]	Fraction of reserves	Years of production
Copper	0.73 kg/kW[b]	$(98+209+11)\times 10^6$	550	16	0.58	20
Lithium	0.3 kg/kWh[c]	8×10^6	4.1	0.027	1.9	290
Nickel	2.5 kg/kWh[d]	66×10^6	70	1.61	0.95	41
Zinc	0.9 kg/kWh[e]	19.7×10^6	180	11.3	0.13	2.1
Platinum	0.004 kg/kW[f]	$31.\times 10^3$	0.07	1.61×10^{-3}	0.44	19

[a] US Geological Survey 2009.
[b] Brush et al. (2002) and Parasility et al. (2004).
[c] Tahil (2006).
[d] Gaines and Cuenca (2000).
[e] www1.duracell.com/oem/primary/Zinc/zinc_air_tech.asp.
[f] Yang (2009).

3.8. *Lithium (Li), nickel (Ni), zinc (Zn) and platinum (Pt)*

Lithium-ion batteries have the largest energy density and, for this reason, are the most used in current electric cars. If the fleet were to be transformed to electric cars with the parameters shown in Table 2, then 8 Mt of Li would be required. Thus, if the current fleet of cars has to be transformed in 30 yr, we would need a lithium production 10 times larger than the current one and 1.9 times the actual reserves would have to be used. Not to mention that the practical totality of the actual demand goes to mobile and PC industries.

Alternatively, nickel batteries Na-NiCl2 (Zebra), and zinc–air batteries are technically feasible. Some commercial motor vehicles have used the Zebra batteries, such as the Modec Electric Van, the Think City and the Renault Twingo Quickshift Electric. As can be observed in Table 2, it would take 41 yr of current global production to equip the fleet with nickel batteries and it would use 95% of the current reserves.

Until very recently, zinc–air batteries have been non-rechargeable. However, the *SINTEF Research Institute* in Norway has developed a new technology to recharge this kind of batteries, which is being currently commercialised by *Revolt Technology Ltd.* for mobiles and computers batteries. If this design were to be adapted to electric vehicles requirements, it would be a realistic alternative to lithium-ion, because Zn is much more abundant that Li. As can be seen in Table 2, only 13% of reserves and 2.4 yr of production at the current rate would be necessary.

Agricultural electric vehicles are being currently introduced in the market. Venieri models ET-400 and VF 263B are examples of this technology. These models may be useful in flat spaces and working conditions with moderate climbs. However, design of models apt to any work condition does not seem an insurmountable task. The number of agricultural tractors in the world has been estimated at 25,680,124 in 2009 (http://www.nationmaster.com/graph/agr_tra-agriculture-tractors), which amounts to 2.6% of the total number of cars. The number of batteries and fuel cells involved in agriculture could be of this order of magnitude and does not contribute perceptibly to the resources estimation made above.

A fraction of the motor vehicles would have to be based on fuel cells instead of batteries due to specific necessity of large autonomy and high power density in some services such as fire trucks, ambulances, police, military vehicles, high power tractors and heavy machinery.

One possible scarce material that is essential for the fuel cells catalysts is platinum (Pt). As can be observed in Table 2, 44% of reserves would be used if 10% of the fleet were powered by fuel cells. To manufacture these vehicles in 30 yr approximately 65% of the current rate of production would be necessary. Again, the scarcity of the resource may put in danger the future deployment of this kind of fuel-cell powered vehicles, since this metal is used in many other applications. However, technology exists to recover 90% of Pt from catalytic converters until new, and more abundant, catalysts are found (Jacobson and Delucchi, 2011).

4. Discussion and conclusions

As recognised by the International Energy Agency in its World Energy Outlook (2010), crude oil production is in a plateau since four years ago and expected to never be increased. After the peak of fossil fuels, the EROEI of energy will quickly decrease and the costs of capital mobilisation will non-linearly increase. A renewable solution would be facilitated by energy conservation measures on the demand side (Jacobson and Delucchi, 2011). Here a long term technical solution to the problem of the Oil Crash has been shown to be affordable in principle with current technologies based on wind turbines, CSP, hydroelectricity and wave devices.

The moment to start the huge technological challenge needed to deploy the renewable solution is now, when societal EROEI is still high, and basic social needs are not competing with industry for capital investment. Nuclear power, gas and coal gasification power could help for some decades to mitigate the general decrease of fossil fuels, but these decades should be employed to build the definitive solution. The first step should be the massive building of wind turbines, the technology that is already almost competitive with fossil fuel power. In fact 13% of the world wind stations have already production costs smaller than fossil-fuel generation, because of their favourable location (Delucchi and Jacobson, 2011). From nowadays to 2030 plausible developments of the current technology would permit deploying offshore wind turbines and floating platforms on continental shelves until 225 m depth. Hybrid wind–wave systems could enhance the yield and power stability of offshore wind turbines and decrease the cost of installation and transmission of wave devices, which could contribute 3.5% of the global demand.

A recent top-down analysis by De Castro et al. (2011) on the energy dissipation in the atmospheric boundary layer has concluded that the wind resource really available is 1 TW globally. If it is confirmed, the solar contribution would have to be increased by a factor 2.1 to match the demand. In this case, the area of the blue and grey dots of Fig. 2 would represent approximately the real areas of CSP needed.

In a few years, CSP will be competitive, being incorporated to the energy mix without needing government support (Fthenakis et al., 2009; Delucchi and Jacobson, 2011), and its massive implementation should be initiated, in parallel with the building of the international HVDC grid.

An approach in the direction of the one proposed here is being promoted via the Desertec Foundation, which has gathered up to 12 industrial partners in order to supply energy to Europe by covering around 6000 km^2 of desert across North Africa with CSP plants using molten salt storage and air cooling. By embarking onto such a large-scale renewable energy strategy, a new form of real economic cooperation with developing nations, which are rich in sun and wind, could be achieved.

Contrary to water cooling, turbine-based air cooling is a technology yet to be developed. If it can be developed in time, it will allow installing CSP plants with storage even in deserts with no available water. An important synergy will be the combination of CSP and wind turbines in shorelines of windy and sunny regions, such as the West Coast of the Sahara Desert. This will permit sharing the same HVDC line to export sun and wind power.

However, to stimulate production of wind and solar energy to the rates needed, new policies are necessary such as feed-in tariffs to stimulate renewable generation, when its production cost is not yet competitive, eliminating subsidies for fossil-fuel energy systems and taxing fossil-fuel production and use (Delucchi and Jacobson, 2011).

Technical solutions to mitigate the consequences of Peak Oil are attainable, but they involve a series of strong consequences for the future of our economic system. First, the need of the almost entire electrification of our society. But this is strongly constrained by materials availability. According to our solution, basic materials are steel, concrete, nitrates, neodymium, copper, aluminium, lithium, nickel, zinc and platinum. Steel, concrete, aluminium and zinc are not limiting factors, but the rest do actually impose serious concerns on the use of material reserves.

For some kinds of windmills, Nd is needed and is almost entirely produced by one country. Its 2001 production rate needs to be increased by a factor 4 for 30 yr. Therefore, the large-scale development of wind turbines should, prudently, be planned on the use of turbines with no permanent magnets. Jacobson and Delucchi (2011) have proposed four technological alternatives that avoid the use of Nd and other REE. The motors of the vehicles fleet could also avoid the use of Nd using switched reluctance designs, for instance, or other induction designs.

For CSP with storage, large scale production of synthetic nitrates should be initiated or alternatively adequate substitution should be implemented. Copper would be intensively used in an electricity based society. Our estimations result in 60–70% of the Cu reserves having to be used to implement a renewable solution. This intensive use of Cu would bring its price close to that of precious metals such as silver, contrarily to the case of Al, which before 1886 was as expensive as silver, due to supply limitations. It does not leave too much room for additional increases of energy demand. A rational strategy would be to employ the remaining 30–40% of Cu for the development of other industrial products and not in additional power production. Currently, ELRR of Cu is 43–53% (UNEP, 2011). These rates could be improved by a strict control of dismantling of obsolete windmills and CSP stations, since metallic Cu can be recycled almost completely without loss of value.

Finally, lithium, nickel, zinc and platinum are essentially metals in the transition from fuel fossil to electricity based transportation system. Here again, serious constraints appear. The Li needed is double the present reserves and 44% of Pt should be dedicated to such transition. Independently of the metal that may conquer the future EV batteries (probably Zn or Ni), the motor vehicles electrification would employ an important fraction of the estimated reserves of the metal. If Ni were to be the option, the current fleet would have to be reduced by an uncertain percentage due to shortages of the resource, except if new resources were made available for the other industrial demands. If Li were to be the option, a drastic reduction of the current number of cars would be needed, allowing as much a fleet as 51% of the current one (which would use 100% of current reserves). This would require that new reserves be made available in the future to satisfy the demand coming from computers and cell phones. In any of the two cases, a powerful recycling system would have to be implemented for Ni and Li, which currently have ELRR of 58–63% and $<1\%$, respectively (UNEP, 2011, pp. 30, 36).

Second, after implementing this renewable power solution, we would have reached a situation where an exponential growth in power production would no longer be possible. Confronted to the material limitations and less-than-100% recycling, growth would be possible only with: i) gradually reducing aggregate demand (while maintaining living standards), by improving use efficiency and changing activity patterns and system design; ii) finding new sources of the limiting materials (e.g., extra-terrestrial sources) or iii) using materials that can be regenerated by primary indefinitely renewable resources (e.g., based on solar energy input) at least at the rate at which the materials leave the recycling system.

Third, production rates and population would have to adapt quickly to a scenario of steady state power production. This scenario, which some authors define as "spaceship economy" (i.e. Boulding, 1993), is incompatible with the current exponential-growth paramount scenario. However, it is not a novelty in the human history. Given that the business as usual is not a sensible alternative after Peak Oil, authorities and civil society should adopt effective measures to initiate the transition to the new system. We should now start to build the definitive renewable solution for the global energy consumption and do it without relying on technical miracles or temporary mitigation.

Appendix A. EROEI

The EROEI of a particular source is the ratio of the total amount of energy produced by this source, E_p, to the amount of energy required as an input to produce it, E_i. For fossil-fuel based energy sources E_p involves energy to find, extract and deliver the fuel and also to build the plant (E_i), and useful energy (E_u) delivered to the society (Fig. A.1).

Then from its definition, we have

$$\mathrm{EROEI} = \frac{E_p}{E_i} = \frac{E_p}{E_p - E_u}$$

Typical values for EROEI of different sources are provided by Heinberg (2009). EROEIs of the different energy sources decline with time, despite technological improvement (Hall et al., 2009). For example the EROI was 100:1 for crude oil at the beginning of 20th Century, 50:1 by 1950 and 20:1 nowadays. The reason lies in the fact that technology usually allows extracting previously inaccessible resources at the cost of increasing the operation

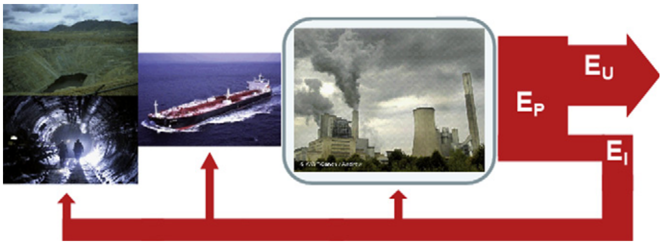

Fig. A.1. General schematic balance of energy production based on a non-renewable primary source.

costs, and the gains due to advances in technology seem to be always offset by the loss in quality of the produced material.

We can also talk about the EROEI of a society, which represents the weighted average of the EROEIs of all the energy sources that nourish the society; the weighting factor for each sources is given by the fraction of energy (with respect to the total) that that source presents. Considering a society (or the whole planet) as a closed system and from the EROEI definition for the whole society we get

$$E_u = E_p\left(1-\frac{1}{\mathrm{EROEI}}\right)$$

The decline of the EROEIs of the different exploited sources implies the decline of societal EROEI, which therefore reduces the energy useful for the society. There are anthropological evidences suggesting that a minimum EROEI must be attained for a society not to collapse. Some anthropologic studies have estimated that hunter–gatherer societies could have globally EROEI values of about 9.6/1 (Lee, 1968). Rain-dependent agricultural systems have values of about 11.2:1; felling and burning agriculture, values of about 18:1 and irrigation agriculture, values of about 53.5:1 (Harris, 1997, Chapter 11: Energy and ecosystem). Values below 5:1 would imply very small fractions of social work and time invested in activities different from energy production, which could not be compatible with a complex society (Hall et al., 2009).

Appendix B. Screening process: the no-go alternatives

The primary energy sources currently available can be grouped in the following 13 categories: oil, natural gas and coal; tar sands and oil shale; biofuels (ethanol and biodiesel); energy from waste; nuclear; hydropower; wind turbines; solar photovoltaic; concentrating solar thermal; passive solar; biomass (continental and marine); geothermal; oceanic wave, tidal and thermal.

Heinberg's (2009) elimination process concedes large importance to renewability. This derives from the intention to solve our energy problem in a way that may be sustainable in the future. For this reason, tar sands, oil shales, coal and natural gas will not be commented on here as an alternative to conventional oil.

B.1. Biofuels

Biofuels derived from land crops, like ethanol and biodiesel, have low EROEI (Murphy et al., 2010), and the land and water required for their production are needed for agriculture. However, due to their good properties as energy carrier, a certain quantity of them could be needed (with hydrogen) to maintain an operative transportation network formed by planes and some terrestrial transports. Alternatively some algae are rich in hydrocarbons and could be cropped in marine shelves, and small-scale laboratory tests throw encouraging results (Mata et al., 2010). However, many problems persist when algae are tried to be exploited at large scale, mainly the high costs per unit area associated with the need of a carefully controlled and optimum nurturing environment, contamination by other species in open ponds and high energy and resources required in bioreactors (Mata et al., 2010). A recent analysis of the life cycle of bioenergy feedstocks indicates that conventional crops have lower environmental impacts than algae in energy use, greenhouse gas emissions and water regardless of cultivation location. These should be areas of active research before algae may be considered as an alternative for replacement of fossil fuels (Clarens et al., 2010; Ahmad et al., 2011).

B.2. Waste

Energy from waste is not scalable; the resource base is likely to diminish as society becomes more energy efficient. Due to this, the non-biodegradable fraction of waste has been excluded from the category of renewable sources (Siemons, 2002).

B.3. Nuclear

Recent reports (Dittmar, 2009) show that there is a critical problem with uranium supply nowadays. Moreover, it will peak somewhere between 2015 and 2035 depending on whether only cheap Reasonably Assured Resources are considered or all reserves, including Inferred resources, are accounted (Fleming, 2007; Energy Watch Group, 2006). Therefore, conventional fission may not be considered as an inexhaustible energy source. Fast breeding reactors (FBRs) could increase the useful life of nuclear fuel; however they are still in a developmental phase. Apart from military reactors (intended for the production of plutonium and having modest or negative breeding rates), just six civil reactors with a combined installed power of 1.6 GW have been operated, mostly as demonstration or pilot plans. The main challenges to be solved about FBRs include security (frequent leaks of the sodium or molten salts coolants), relatively scarce power and low breeding ratios (Dittmar, 2009, Part IV: Energy from breeder reactors and from fusion?). On the other hand, management of nuclear high activity waste is a problem that will require indefinite monitoring and control, endowing an economic burden, not yet quantified, on the future generations. Nuclear fusion has not been considered here because it is a technology under research, which could become economically viable only between 2060 and 2100 (Tokimatsu et al., 2003, Llewellyn and Ward, 2008).

B.4. Biomass

Biomass energy production is limited in scalability by available land and water and tends to compete with other uses of biomass for food. Sustainability of biomass-based energy requires major efforts as overexploitation of biomass resources occurred even before the industrial revolution. Reijnders (2006) concludes that up to 3 t/ha/yr of biomass could be gathered in tropical and temperate woods without major ecological impacts. It is equivalent to 5 TW of heat power globally. However, necessity to avoid climate impacts as well as to maintain soil depth, soil organic matter, soil nutrients and fresh water, makes implementation of global extraction, in the terawatt range, of biomass primary energy very uncertain.

B.5. Passive solar

The use of passive solar heating and cooling does not generate any surplus energy to industrial or transportation use and, for this reason, cannot be considered a global source of primary energy. However, it involves no materials with significant limitations and it is potentially very important for domestic energy saving fractions in the range 50–89% (Givoni, 1991; Fernández-González, 2007). In addition, PV panels in roofs and heliostats in large areas may help to reduce or eliminate the electricity budget of homes and commercial areas (Rohr, 2009).

B.6. Tides, currents, waves and ocean thermal

Two methods are being tested to generate electricity from tides: barrages and tidal stream generators. Tidal barrages accumulate water potential energy through the use of dams across the full width of a tidal estuary. The experience with barrages has shown that they should be placed in narrow estuaries with a tidal range of, at least, 5 m. Only a few sites in the world are suited to install these barrages, and some of them are located far away from demand centres (Baker, 1991). This fact, together with the detrimental ecological and landscape impacts of this system, puts a limit on the amount of energy to be generated by barrages. Today, around 250 MW are produced by barrage plants in the world (from which 240 MW comes from a single barrage, at Rance in France). An alternative to tidal barrages, stream generators, whose principle is very much like the one of aero-generators, can be placed in sites where ocean currents are 1 m/s or larger. Most of the stream generator technology is in a prototype stage; therefore, its scalability is still unclear. However, wave power (see Section 2.1) as well as Ocean Thermal Energy Conversion (OTEC) could be excellent complements to offshore wind turbines.

OTEC is currently expensive in capital (8100 2002-$/kW for plants 200 km offshore) and electricity supplied (0.13 2002-$/kWh for the same conditions; Vega, 2003). In addition, they get their largest efficiencies (3–4%) only in tropical waters, where hurricanes are frequent. Some flexible or articulated pipe technology for deep waters able to resist these weather conditions remains to be proven. However, it could add about 1 TW to the mix when these handicaps were overcome. According to Nihous (2007) the resource available is 2.7 (secular scale) to 5 TW (short term) with 16×10^6 m^3/s of deep water pumping (160,000 pumps of 100 m^3/s). However, this CO_2-rich upwelling is of the same order of magnitude as the Overturning Circulation, which may produce disturbances on pelagic ecology and global climate.

B.7. Geothermal

Geothermal electricity generation is unlikely to be scalable. Although 1390 PWh yr^{-1} could be reached, the technical potential is about 0.57–1.21 PWh yr^{-1} due to cost limitations (Jacobson, 2009). While geothermal heat pumps can be used almost anywhere, they cannot produce a primary power for transport or electricity grids.

B.8. Solar photovoltaic (PV)

Solar photovoltaic power may be scaled up potentially to many tens of terawatts (Feltrin and Freundlich, 2008). However, it is still expensive and it relies on rare materials such as silicon, cadmium, tellurium, copper indium selenide ($CuInSe_2$) and copper gallium selenide ($CuGaSe_2$), whose depletion could limit deployment of the technology. Limited supplies of tellurium and indium (as a consequence of new environmental regulations, particularly in China) reduce the prospects for some types of thin-film solar cells, though not for all. The question remains as to whether the other types of solar technologies might be able to make up the shortfall. Silicon is abundant, but polycrystalline silicon cells are limited by scarcity of silver used in the electrodes (Feltrin and Freundlich, 2008). Solar PV technologies with optical and luminescent concentration promise to mitigate some of these difficulties because they decrease the surface of cells needed for electricity production (Kurtz, 2009). However, to date, the possibility to scale up PV power to the terawatt range depends on the success of research in reduced use of silver as well as in new developments based on no scarce materials with marketable prices. Wadia et al. (2009) conclude that three PV technologies are well suited to satisfy those two conditions: pyrite (iron sulphide, FeS_2), Zn_3P_2 and a-Si. All these systems would be part of the future mix as soon as they reach marketable efficiencies and cost, and they get to improve the low EROEI that characterize other PV systems of about 2.7:1 (Prieto and Hall, 2011) to 10:1 (Gupta and Hall, 2011). EROEIs of cells based on FeS_2 remains to be documented; however it should be much higher than those of usual PV systems since pyrite is a common material.

Appendix C. Assumptions and parameters used in the calculation of the Cu utilisation for production and transmission in wind farms

Taking as a reference the Vestas-V90 of 3 MW, Nalukowe et al. (2006) estimated the copper content of generator, gearbox, structure and machinery. Table C.1 shows the main figures. From it, it can be found that 1.57 t/MW is used in this kind of DFIG turbine.

Direct Drive Permanent Magnet (DDPM) generators and Direct-Drive Synchronous (DDSM) generators have also been designed to avoid the use of gearboxes. However, the use of permanent magnets that contain Nd may be an unsurpassable obstacle to the global scale of the former design. DDSM designs seem more promising. However, Bang et al. (2009) have estimated that 12.6 t of copper is required for a 3 MW generator with this kind of design, which means 4.2 t of copper per MW, more than 4 times the requirement of a conventional DFIG design.

To calculate the copper in the low voltage power transmission from the generator to the MVT we will take as a reference the wind turbines of the Peña Armada and Do Vilan wind farm, in Spain. Each 55 m high, 1.3 MW wind turbine needs a $3 \times 3 \times 240$ mm^2 copper line to reach the base of the tower. The splitting of the transmission into three different three-phase conductors instead of a single one allows more flexibility in the cables, which hang close to the vertical rotation axis of the windmill. Taking the copper density to be 8.92 t/m^3, we obtain that 0.82 t/MW is required. Some models have the low–medium voltage transformer in the nacelle and they can save this fraction of copper.

To calculate the copper needed for the windmill earthing system we will assume three concentric rings of nude copper with section 70 mm^2 and radius 7.2 m, 8.2 m and 9.2 m for a 1.5 MW turbine. The copper mass obtained is 64.7 kg/MW or 0.065 t/MW.

The copper required from the wind farm equipotential low resistance earthing grid is very variable due to the different geometries of wind farms. We have taken the nominal power and the underground medium voltage (MV) grid of 12 different wind farms in Spain and one in Chile, to obtain an average figure. The wind farms are the following: Salce (León), Curueña I (León), Baños de Ebro (Álava), Project for Puerto de Bilbao, Jata (Bizkaia),

Table C.1
Parameters of the Vestas-V90 3 MW turbine (from Nalukowe et al., 2006).

	Weight (t)	% Cu	t-Cu/MW
Generator	8.5	35	1
Gearbox	23	1	0.08
Structure, machinery	37	4	0.49
Total			1.57

Table C.2
Average copper utilisation in 12 onshore wind farms.

System	t-Cu/MW
Low voltage power transmission	0 or 0.82
Windmill earthing system	0.065
Windfarm earthing grid	0.18

Dolar-3 (Granada), Gazume (Guipúzcoa), Canto Blanco (País Vasco), Peña del Gato (Castilla-León), Villanueva, Jaulín (Zaragoza), Valdelarroñada (Castilla-León) and Laguna Verde (Valparaíso). The assumption is that one 50 mm^2 copper cable goes with the three-phase MV grid. The figure obtained is almost 400 m/MW of cable with weight 0.18 t/MW (Table C.2).

Adding all the contributions, 2.7 t/MW of copper is required for wind farms with standard windmills and 1.85 t/MW if the windmills have the LV/MV transformer in the nacelle.

Appendix D. Copper used in the HVDC transmission

Typically, a bipolar 5 GW ± 800 kV line has a power loss of 2.5% per 1000 km overhead and similarly in sea cables. Terminal losses are about 0.6% per station (Trieb, 2006, p. 24).

Typically, a bipolar HVDC line transmitting 10 GW uses the materials inputs showed in Table D.1. "Impregnation" refers to the oil and wax that impregnate the paper used to insulate the copper core and to exclude moisture. Alternative dielectric materials that have been used instead of oil and paper include synthetic resins and synthetic polymers.

As can be observed in Table D.1, only submarine cables use Cu as the main conductor. Overhead cables use Al and steel.

From the paths shown in Fig. 2, only those transporting power to Europe and South Asia include submarine segments. Trieb (2006) reports the length of the three main HVDC paths crossing the Mediterranean Sea from Africa and their submarine segments. These paths are shown in Fig. 2 and their initial points are connected to each other by a horizontal HVDL line crossing the Sahara desert. We will assume that each of these paths carries 1/3 of the power needed by Europe, in HVDC bipolar lines of 10 GW (making almost 22 lines in every path). A submarine path of 4000 km has been assumed also between Australia and Asia. For the rest of world, only one path connecting the production and consumption region will be used in the calculation. All these paths are assumed to be made up of lines of 10 GW.

Table D.1
Materials input used in the large distance electricity transport (based on Trieb, 2006, p. 138).

HVDC 10 GW	**± 800 kV overhead, 2 lines** (t/km)	**± 800 kV submarine, 8 cables** (t/km)
Aluminium	2 × 17.4	
Steel, high grade	2 × 6.4	8 × 24
Steel, low grade	2 × 75	
Concrete	2 × 200	
Ceramics	2 × 2	
Copper		8 × 19
Lead		8 × 17
Polypropylene		8 × 2.3
Paper		8 × 6
Impregnation		8 × 1

We assume that a single line between the mass centre of production region and the mass centre of the consumption region transporting the whole demand uses the same amount of copper that many connection lines transporting power to different consumption points do.

Table D.2 shows the characteristics of the main paths connecting production and consumption regions. Column 3 shows the fraction of the global power demand (11.5 TW) that flows along the corresponding path. For solar production regions, this figure is the share of solar power in the mix (0.4) times the weight of the consumption region in the world. These weights have been obtained from the IEA (2009) predictions for the 2030 consumptions by world regions. For wind production areas (Iceland, North Sea and Kuriles), the fraction transmitted is the fraction of regional consumption that flows along the path (assumed to be 0.05, 0.75 and 0.05, respectively) times the weight of the corresponding consumption region, times the share of wind power in the mix (0.51).

Column 4 shows the approximate lengths of the main paths connecting production and consumption regions. The origin and end of the paths are assumed to be the centre of mass of the production and consumption region, respectively. Columns 5–7 correspond to the installed capacity of Stirling and air-cooled CSP stations (column 5), CSP stations with storage (column 6) and offshore windmill farms (column 7) able to supply the demand after taking into account transmission losses. Column 8 shows the percentage of load losses in every path.

These installed capacities have been used to calculate the number of stations and turbines displayed in Table 1 (column 5), as well as the soil surface needed to install the CSP stations. The areas obtained for stations of diurnal (nocturnal) demand have been multiplied by a factor 2 and then displayed in the blue (grey)

Table D.2
Production regions (column 1) and associated consumption areas (column 2) connected by HVDC lines. Column 3 shows the fraction of global demand (11.5 TW) that is supplied from the specified production region to the corresponding consumption region (see text). Column 4 represents approximate distance between the centre of mass of the production region and the one of its corresponding consumption region. Columns 5–7 correspond to installed capacity of Stirling and air-cooled CSP stations (column 5), CSP stations with storage (column 6) and offshore windmill farms (column 7) able to supply the demand after taking into account transmission losses. Column 8 shows the percentage of load losses in every path.

Production region	**Consumption region**	**Power fraction**	**Total length (10^3 km)**	**Undersea length (km)**	**Power Stirling** (GW)	**Power storage** (GW)	**Power turbs** (GW)	**Per cent losses in the path**
Chile	South America	0.05 × 0.4	2		171	73		6.3
Sahara	EU, Ukraine	0.14 × 0.4	3.1/3.1/5.1	18/373/30	505	217		10.1
North America	North America	0.18 × 0.4	2		622	267		6.3
Middle East	Middle East	0.06 × 0.4	2		215	92		6.3
India	India	0.08 × 0.4	1		263	113		3.7
Asia	China, Russia, Japan	0.37 × 0.4	2.5		1296	556		7.5
Australia	Australia	0.08 × 0.4	4	4000	298	128		11.3
South Africa	South Africa	0.03 × 0.4	1.5		90	39		5.0
Iceland	EU	0.05 × 0.14 × 0.51	3.5	2000			32	10.0
North Sea	EU, Ukraine	0.75 × 0.14 × 0.51	1.5	1000			461	5.0
Kuriles	Japan	0.05 × 0.37 × 0.51	2	2000			82	6.3
Rest of continental shelves	World	0.87 × 0.51	0.024	24			3606	1.3

dots of Fig. 2. The radii in km of these circles for diurnal (nocturnal) demand are: 88 (37), 152 (64), 169 (98), 99 (42), 110 (46), 273 (141), 117 (49) and 64 (27), respectively, for every solar production region referred to in column 1 (files 2, 3, 4, 5, 6, 7, 8 and9) of Table D.2.

With the above assumptions, and the lengths and weights given by Table D.2, the amount of Cu needed to build this simplified HVDC transmission system is estimated to be 40 Mt.

Appendix E. Copper used in the railway system

The current global railways system has been estimated to be 1,136,015 km in 2006 (see http://www.nationmaster.com/graph/tra_rai_tot-transportation-railways-total). To estimate the amount of Cu required for the electrification of this grid, the catenary CR-220 used in the electrification of Spanish railways (Montesinos, 2010) is taken as a reference. In this catenary, 4.3 t/km of Cu is used (a standing cable of 153 mm^2 and two contact cables of 107 mm^2) for conventional railways. For high-speed railways, four Cu cables are used, employing about 10 t of Cu per kilometre (European Copper Institute, 2007). Assuming a share of 50%, 25% and 25% of single, double and high-speed-double world railway, respectively (Table E.1), the mass of Cu required would be of 10.6 Mt. Additionally, the use of Cu in trains has been estimated to be 1–2 t and 3–4 t in conventional and high-speed trains, respectively. If one high-speed train is assumed for every 50 km of high-speed railway and one conventional train is assumed for every 33 km of normal railway, the copper used in the railway system ascends to 110,000 t.

Table E.1
Parameters used to calculate Cu in railway system.

	Single catenary	Double catenary	Double high speed catenary
Cu content (t/km)	4.3[a]	2×4.3[a]	2×10[b]
% Railways	50	25	25
Length (km)	568,008	284,004	284,004
Locomotives number	1/33 km	2/33 km	2/50 km
Cu in locomotives	1.5[b]	1.5[b]	3.5[b]

[a] Montesinos (2010).

[b] European Copper Institute (2007).

Table F.1
Classes of EV (column 1), typical weight (column 2), global number in 2011 (column 3), typical peak power of its battery (column 4) and battery capacity (column 5).

Kind of EV	Empty weight (kg)	Number in 2011 (millions) [a]	Power (kW)	Battery capacity (kWh)
Light	1200	584	60[b]	22.4[c]
Heavy	5155[d]	240	179[d]	67[e]
Motorcycle	200	271	3.6[f]	1.2[f]

[a] Based on Walsh (2005).

[b] Based on Westbrook (2001.

[c] Based on the mean Wh/km of 8 commercial EV described in http://es.wikipedia.org/wiki/.

[d] Parameters of the Isuzu FVR, from (Tomich 1999).

[e] Extrapolated from the reference in footnote c with the rate of peak powers between heavy and light EV.

[f] Parameters of the Modenas CTric (see http://www.modenas.com.my/v2motorcycle.asp?id=79).

Appendix F. Copper used in the EV fleet

A new conventional car has about 2% of copper in its structure and equipment (based on data from USGS Fact Sheet, 2009; Association for Science Education, 2011) and the copper content of an electric motor is about 0.73 kg/kW (based on Parasiliti et al., 2004; Brush et al., 2002).

The capacity of the batteries used by current light vehicles ranges between 8 kWh of the Toyota Prius and 53 kWh of the Tesla 70 EV. The average consumption of eight different commercial electric car models is about 14 kWh per 100 km (http://es.wikipedia.org/wiki/Vehículo_eléctrico), and typical autonomy is between 100 and 480 km. However, Gaines and Nelson (2009) cast doubts about the marketability of EVs with ranges much greater than 160 km. Therefore, we will take this figure as the typical autonomy of light and heavy EVs.

Typical light vehicles power ranges between 2.6 and 20.6 kW, with 8–10 times larger peak power (25–200 kW; see Hereward, 2005). We will take 60 kW as a typical peak power of a light EV.

A typical heavy vehicle is the Isuzu FVR, with 179 kW and 5155 kg of empty weight, a multipurpose truck for urban work and interurban trade for short and medium distances (Tomich, 1999). We will take 179 kW as a typical peak power for a future heavy EV. We will take 3.6 kW as a typical peak power for a motorcycle and 1.2 kWh for its battery capacity. This coincides with the parameters of the scooter "Modenas CTric" (see http://www.modenas.com.my/v2motorcycle.asp?id=79). Table F.1 summarises the parameters used in the calculation.

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