Planet Ocean
J.L. Pelegrí and D. Vaqué (eds)

SCIENTIA MARINA 80S1
September 2016, 257-268, Barcelona (Spain)
ISSN-L: 0214-8358
doi: http://dx.doi.org/10.3989/scimar.04295.12A

Energy for a sustainable post-carbon society

Antonio García-Olivares

Instituto de Ciencias del Mar, CSIC, Ps. Marítim de la Barceloneta 37-49, 08003 Barcelona, Spain.
E-mail: agolivares@icm.csic.es

Summary: A feasible way to avoid the risk of energy decline and to combat climate change is to build a worldwide, 100% renewable energy mix. Renewable energy can be scaled up to the range of 12 electric terawatts (TWe) if 10% of continental shelves are exploited with floating turbines to depths as low as 225 m, 5% of continents with ground turbines, and 5% of the main deserts with concentrating solar power (CSP) farms. However, a globally electrified economy cannot grow much above 12 TWe without approaching the limit of terrestrial copper reserves. New photovoltaic silicon panels do not use silver metallization pastes and could contribute up to 1 TW of decentralized residential power. Hydroelectricity has a potential of 1 TW but a fraction of this would have to be sacrificed for energy storage purposes. Hydro, CSP, wave energy and grid integration at continental scales may be sufficient to fit supply to demand, avoiding intermittency. The renewable energy mix would have an energy return on energy invested about 18, which is 25% lower than the estimated present one. That should be sufficient to sustain an industrialized economy provided that the substitution of electricity for fossil fuels is done intelligently.

Keywords: 100% renewable energy; renewable potential; EROEI; material limits; post-carbon economy.

Energía para una sociedad post-carbono sostenible

Resumen: Una forma posible de evitar el riesgo de declive energético y luchar contra el cambio climático sería construir un sistema energético global 100% renovable. Un sistema de energía renovable (ER) se podría escalar hasta el rango de 12 terawatios de electricidad (TWe) si el 10% de las plataformas continentales fueran explotadas con molinos flotantes hasta profundidades de unos 225 m, 5% de los continentes con turbinas terrestres, y el 5% de los principales desiertos fueran utilizados para estaciones de concentración solar (CSP). Sin embargo, una economía electrificada a nivel mundial no puede crecer muy por encima de 12 TWE sin acercarse al límite de las reservas globales de cobre. Los paneles fotovoltaicos (PV) de silicio más recientes no utilizan metalizaciones de plata y podrían contribuir con hasta 1 TW de energía residencial descentralizada. La hidroelectricidad tiene un potencial de 1 TW aunque una fracción de ello tendría que ser sacrificado con fines de almacenamiento de energía. Hidroelectricidad, CSP, energía de las olas y redes integradas de escala continental pueden ser suficientes para ajustar la oferta a la demanda, evitando la intermitencia. El nuevo mix eléctrico tendría una Tasa de Retorno Energético (TRE) de alrededor de 18, un 25% menos que la TRE actual estimada. Eso debería ser suficiente para sostener una economía industrializada, siempre que la sustitución de los combustibles fósiles por electricidad se haga de forma inteligente.

Palabras clave: Mix 100% renovable; potencial renovable; TRE; límites materiales; economía post-carbono.

Citation/Como citar este artículo: García-Olivares A. 2016. Energy for a sustainable post-carbon society. Sci. Mar. 80S1: 257-268. doi: http://dx.doi.org/10.3989/scimar.04295.12A

Editor: J.L. Pelegrí.

Received: June 16, 2015. **Accepted**: November 24, 2015. **Published**: September 30, 2016.

INTRODUCTION

Some of the major challenges that the present world economy faces are energy security, sustainability, degradation of natural resources and climate change impacts. There is rising evidence pointing to the proximity of a peak in global oil supply (Mearns 2011, Murray and King 2012, Chapman 2013, García-Olivares and Turiel 2013) and other authors forecast that the peak of fossil fuel production may occur within a few decades (Leggett and Ball 2012, García-Olivares and Ballabrera-Poy 2014, Pleßmann et al. 2014). This is a significant risk to energy and human security and makes it urgent to find viable substitutes for fossil fuels. Some authors have studied the pros and cons of potential energy alternatives (Heinberg 2009, Jacobson and Delucchi 2011, García-Olivares et al. 2012) and their conclusion is that, given the limits of nuclear reserves and their associated environmental problems, a promising way to face the risk of uncontrolled decline of energy supply is to build a global completely renewable energy (RE) mix. The transition to a post-carbon society based on a renewable mix has also been defended as a means to combat climate change, and to combat the environmental degradation and "externalities" produced by an economy based on fossil fuels (IPCC 2011, Singer 2011, Barzantny et al. 2009, Lehmann and Nowakowski 2014, Creutzig et al. 2014).

The materials required to deploy a 100% RE mix are essentially steel, concrete, aluminium, copper, nickel, lithium, platinum and nitrates (García-Olivares et al. 2012). Silver can be replaced by aluminium in concentrated solar power (CSP) mirrors and by copper and nickel in last-generation crystalline silicon photovoltaics (PV) (García-Olivares 2015a), neodymium may be avoided by using electromagnets in generators, and nitrates may be synthesized from nitrogen by using a fraction of the energy supplied from the CSP stations. Present reserves of Fe, non-metallic minerals, Al, Cu, Ni and Pt are sufficient to initiate such an RE transition, but they may constrain the growth of an RE mix over a mean power of 12 TW (García-Olivares et al. 2012). In particular, García-Olivares et al. (2012) showed that a wholly electrified economy consuming 11.5 TWe at the end uses is technically possible but it would use about 330-380 Mt of copper, which amounts to 50% of the present reserves (700 Mt according to USGS 2015). This means that such a renewable deployment would be possible, but that further growth for other industries that depend on copper would be catastrophic. Thus, a 100% renewable economy cannot be based on an exponentially growing consumption of materials. And given that dematerialization is apparently not able to progress at an exponential pace in the present economic system, a steady-state economy would be the necessary complement to the 100% renewable mix, even under business-as-usual premises (García-Olivares and Ballabrera-Poy 2014).

Other authors are optimistic regarding technology and consider that the use of breeder reactors, fusion or some other technological novelty could indefinitely postpone primary energy decline. Thus, any limitation that renewable resources may pose would be overcome by future technological innovations. This hope is not credible however, because new technologies and energy systems take about 50 years to diffuse throughout the economy (Fouquet 2010). Therefore, the new energy systems that will replace fossil fuels in 50 years are most probably those that are currently being tested, i.e. renewables.

Some studies (Heinberg 2009, 2014) have warned of the urgent necessity for an RE transition, and have also emphasized the enormous difficulty that it involves. These difficulties are of three kinds: (i) the wide social consensus and enormous economic investment required before fossil fuel decline causes economic damage; (ii) the difficulty of obtaining levels of power with renewable sources that are similar to what the present mix produces; (iii) the difficulty of fully replacing the services that the current economy provides with other equivalent services provided by an electrified economy.

If a future post-carbon society is capable of sustaining an industrial developed economy, it must solve problem (ii) and it must find a way to implement the appropriate process substitutions summarized in (iii). The problem described in (i) is essentially a political problem. It involves presenting the renewable transition to the stakeholders as an option that solves some of the sustainability problems mentioned above and does not cause such high social opposition as other alternatives such as nuclear energy; and it also requires that this option receive enough support and no strong opposition from these stakeholders.

Problems (ii) and (iii) also involve political decisions and power relationships in the process of being solved, and require a technical analysis to decide whether they have feasible solutions. In this paper, we focus and discuss the technical aspects of the problem (ii) and in a complementary article (García-Olivares 2015b) we study problem (iii).

The realization of this 100% RE transition depends on many political variables. The present analysis must be considered as a technically feasible proposal that can be made from the scientific-technical world to politicians and stakeholders and that, to be implemented, requires political will and popular support. In this regard, it can be considered as a piece of "post-normal science" as defined by Funtowicz and Ravetz (1993) and "foresight knowledge" (Frame and Brown 2008).

The manuscript is organized as follows. The next section reviews the present discussion on the limits of RE and the most promising sources of RE, and concludes that a mean production of 12 TW power is feasible with an RE mix based mainly on wind, CSP, PV energy and hydroelectricity. The role of PV residential sources and its possible integration with centralized RE sources in large smart grids are analysed. Then, another section studies the variability of RE sources and some technologies capable of mitigating it, and emphasizes the importance of hydro and CSP sources to match supply to demand. Another section discusses the concept of energy return on energy invested (EROEI), and the possible limitations that a low EROEI of renewables may impose on a future RE mix. The final section summarizes the main conclusions obtained from the analysis.

THE POTENTIAL OF RENEWABLES AND A GLOBAL 100% RENEWABLE MIX

Several studies show that solar, wind and hydroelectricity are the RE technologies best suited to become alternatives to fossil fuels (Heinberg 2009, Jacobson and Delucchi 2011, García-Olivares et al. 2012). Jacobson and Delucchi (2011) concluded that 11.5 TW of mean annual electric power would be sufficient to supply the services that 17 TW of fossil fuels are capable of providing. This was based on the greater efficiency of electricity in electric motors and heating, some probable energy-conservation measures, and energy savings coming from petroleum refining. However, Roadmap (2010) estimates that energy-conservation measures will be compensated for by approximately equal expenditures of hydrogen and gas production for transport, and maintenance of a larger electrical infrastructure, at least in Europe. If the last estimate is right, 12 TWe of future energy input to the end uses would be equivalent to the secondary energy input to these sectors in 2008. De Castro et al. (2011, 2013) consider it implausible that 11.5 TWe or 12 TWe may ever be produced with RE because they estimate the world potential of wind and solar power to be 1 TW and 2-4 TW, respectively. However, these estimates are probably too conservative for the reasons commented on below.

Global wind potential

The global wind potential estimate by De Castro et al. (2011) rightly pointed out the need to use top-down approaches that are able to conserve the total energy flow. However, it is not a consistent top-down estimate, since it presupposes that the power that a wind farm is able to remove from the wind field has to be a fraction ("small") of natural dissipation in the lower 200 m of the atmospheric boundary layer (ABL), which is not accurate. Miller (2011) also assumes that wind farms cannot increase ABL dissipation, arguing that the atmosphere is already at its maximum rate of dissipation according to the maximum entropy production (MEP) principle. It is not generally accepted that the MEP is a universal principle for non-equilibrium systems (Grandy 2008) or the climate system (Pascale et al. 2012). But, even if it were, MEP states that the non-equilibrium flow self-organizes in such a way that the rate of entropy production tends to be the maximum one compatible with prescribed thermodynamic forces and boundary conditions (Ziegler 1983, Niven 2009). An example of thermodynamic force in the atmosphere is mechanical stress. The introduction of a layer of turbine blades over the Earth's surface increases the stress close to the surface boundary and can thus be considered to be a new boundary condition and thermodynamic force. Therefore, the dissipation should change to a new maximum.

In fact, if a new sink of mechanical energy appears in the atmosphere, produced by an extensive layer of windmill blades, the deformation of the wind field increases above the upper blades, as does the momentum and energy that flows vertically into it (see, for instance, the large eddy simulation study of this process made by Calaf et al. 2010). The increased drag makes the force balance within the ABL slightly more sub-geostrophic, and hence increases the work done by the mesoscale pressure gradient on the wind field. As a result, a larger fraction of atmospheric potential energy is transformed into kinetic energy to compensate for the increased loss of kinetic energy. This process is of course unable to compensate 100% for the increased loss of kinetic energy and, for this reason, the wind decreases in speed close to the layer of the mills. The only way to precisely simulate this second part of the process is to resort to models of synoptic scale such as

Table 1. – Surface of areas of continents and respective continental shelves with depths between 0 and 225 m.

Region	Continental surface area (km^2)	Shelf surface area (km^2)
1. Europe	10180000	2146909
2. India, Arabia, Somalia	7652217	968340
3. Asia except 2	36926783	5784000
4. North America	24709000	2320860
5. South America	17840000	2691390
6. Africa	30221532	1484362
7. Australia and New Zealand	7960704	2484500
Total	135490236	17880361

atmospheric global circulation models (AGCM). Thus, to precisely quantify the speed decrease over the blade layers we should ideally use a large eddy simulation model of the wind farm nested within an AGCM or, at least, an AGCM with some idealized model of the blade layer. Adams and Keith (2013) reviewed the predictions of several AGCMs of the alteration of the large-scale wind field by large wind farms, and their conclusion was that power production tends to saturate at a value of 1 W per square metre of surface for wind farms larger than many hundreds of km^2. For individual wind farms the mean power removed may be larger than this, and figures of 4-7 W m^{-2} are frequently observed, but the asymptotic potential for surface coverage tending to infinity goes down to the value of 1 W m^{-2} of electrical extractability.

Continental areas, aside from deserts and mountainous terrain, are used to great extent for economic activities, and combining these activities with wind power extraction will not always be possible. This is not the case with continental shelves, which offer good wind potential. Colonizing continental shelves down to 225 m depth with foundations and floating offshore windmills seems feasible in the next few decades, since the Hywind project of Siemens and StatoilHydro has already succeeded in anchoring turbines 220 m off the east coast of Karmøy, Norway. Table 1 shows the surface area of continental shelves with depths between 0 and 225 m, calculated from the ETOPO1 global relief model (Amante and Eakins 2009), as well as the surface areas of the respective continents. Only latitudes with no ice in winter were considered to quantify shelf surface.

We will assume three scenarios of increasing surface occupation by wind turbines. In the low occupation scenario, wind turbines will occupy 10% of shelves and 5% of continents; in the medium occupation scenario, they will occupy 25% of shelves and 10% of continents; in the high occupation scenario they will occupy 50% of shelves and 20% of continents. Table 2 shows the wind potential obtained for the three scenarios for the seven regions defined in Table 1.

Global solar potential

Regarding solar potential, using subtropical deserts may be crucial since their capacity factors (CF) may be as high as 0.9 (Trieb 2006), and these surfaces are largely unused. García-Olivares et al. (2012) showed that only a minor fraction of the subtropical deserts

Table 2. – Wind potential in three scenarios of increasing occupation of continental and shelf surfaces.

Region	Low Power (TW)	Medium Power (TW)	High Power (TW)
Europe	0.7	1.6	3.1
India, Arabia, Somalia	0.5	1.0	2.0
Asia (except prev.)	2.4	5.1	10.3
North America	1.5	3.0	6.1
South America	1.2	2.5	4.9
Africa	1.7	3.4	6.8
Australia, New Zealand	0.6	1.4	2.8
GLOBAL	8.6	18.0	36.0

Table 3. – Solar power extracted from CSP stations in different regions if 5 TWe were to be produced globally.

Region	Solar production (TW)	Area used (km^2)	Area of desert (106 km^2)	Fraction of desert used
Europe, Maghreb	0.7	93478	9.0	0.01
South America	0.25	31510	0.14	0.23
North America	0.9	130000	0.69	0.19
Middle East	0.3	39718	1.55	0.03
India	0.4	47346	0.2	0.24
Asia except India	1.85	321196	0.63	0.51
Australia	0.4	54949	1.35	0.04
South Africa	0.15	16652	0.98	0.02
Total	4.95	734849	14.54	0.05

would have to be used in order to produce 9.2 TW worldwide with CSP. To be precise, the production of 0.7 TWe with CSP would require 1% of the surface area of the Sahara, i.e. 93478 km^2, or a square box with approximate dimensions of 306×306 km. Other highly insolated deserts such as the Atacama, Arabian and Syrian, Kalahari, Australian, Thar, Gobi, Sonoran, Mohave and Chihuahuan deserts, have similarly important potential (Table 3). High-voltage direct current connections between 2000 and 5000 km in length would be needed in some cases, producing electrical losses greater than 10%. This loss does not preclude the use of this technology, but it does force the solar field installation to be 10% larger than it would be without the long-distance connections.

De Castro et al. (2013) argue that CSP deployment may be limited by the use of silver in mirrors (30×10^3 t per kWe). Given that present reserves of silver are 520000 t, to produce 8 TWe with CSP in deserts would require roughly 46% of the reserves, which may strongly perturb the market and future availability of silver. However, aluminium-coated mirrors could replace silver mirrors if this metal becomes expensive. If we convolve the reflectivity of a silver (and aluminium) commercial mirror (see https://www.thorlabs.de/newgrouppage9.cfm?objectgroup_id=890) with the solar spectrum at the Earth's surface, the integrated reflectivity obtained for aluminium is 14% lower than that of silver. This lower performance could be compensated for by oversizing the solar fields by 14%. This does not seem a serious limitation for a future deployment of CSP, given that the world subtropical deserts are many times larger than the area required for CSP production. The main problem associated with this technology may be that it requires a major investment in electrical interconnectivity and super-grids which would not be easily affordable in the short term.

Thus, even the totality of the 12 TW that García-Olivares et al. (2012) consider compatible with metal reserves could be supplied with CSP in a post-carbon economy if this technology were the only RE source available. Table 3 shows the solar potential for different regions if 5 TW of solar power (4.95 TW for the main continents) were to be extracted from deserts. The expected consumptions of each region, relative to the global consumption, are assumed to be 0.14 (Europe and Maghreb), 0.05 (South America), 0.18 (North America), 0.06 (Middle East), 0.08 (India), 0.37 (Asia except India and Middle East), 0.08 (Australia) and 0.03 (South Africa) (García-Olivares et al. 2012).

In Asia (without India and Middle East) there are no large subtropical deserts, but the Tibetan Plateau has great solar potential that could be exploited with a combination of PV and CSP stations (Kawajiri et al. 2011, Ummel 2010). We have assumed 25% of that region to be available as "area of deserts" in the 4th column of Table 3. As can be seen, Asia would need to use 1/8 of the Tibetan Plateau to supply its solar energy demand, which could put great pressure on the local economy of Tibet. A way to avoid that pressure would possibly be to supplement a fraction of the large East Asian solar demand with electricity imports from Australian deserts.

Photovoltaic potential

Until recently, the scaling-up of PV energy to the terawatt range was not feasible because crystalline silicon PV used about 8.2 g of silver per m^2 of panel (Grandell and Thorenz 2014), so the production of a few terawatts would exhaust global silver reserves. However, in recent years several new technologies that succeed in avoiding the use of silver in solar modules have come onto the market (García-Olivares 2015a). These developments, and the recent sharp decrease in panel prices, are opening the door to a rapid and wide spreading of PV energy. The latter study estimates that up to 1 TW of PV power could be installed in urban regions without perturbing land use; this is 8% of global power (12 TW), which we take to be feasible. To achieve this, 12.5% of world urban surface area would have to be used for PV panels, requiring an increase in the present availability of suitable roofs, which is currently as low as 2% (La Gennusa et al. 2011). Away from municipal areas, space is restricted by farm use. However, if 300000 km^2 were used for a global utility-scale PV installation, one additional TW could be obtained with a power density of 3.3 We m^{-2} (De Castro et al. 2013). This surface would be similar to the one used for populated area (Schneider et al. 2009), 276000 km^2, but is three orders of magnitude smaller than the continental surface area. Thus, it should not be a problem to adapt 0.1% of the continental surface area for this new use in areas not used for agriculture. Thus, in addition to roof panels, each municipality could have associated solar PV farms of a similar areal extent to itself. Governments and municipalities would play an important role in regulating the land use for economic activities and the use of urban space for PV installation.

Decentralized PV production versus centralized RE production

Many roof panels could be owned by households or belong to small-scale energy cooperatives. Thus, decentralized PV production could enhance people's empowerment and autonomy from large energy producers, reduce energy poverty and take us closer to a situation of enhanced energy access for common people that has been called "energy democracy" (Scheer 2012). These are good arguments that common people and social movements should use to persuade governments to support decentralized production and self-consumption. Governments of many countries (e.g. Germany and Denmark) have done so in the last decade by subsidizing RE. A combination of support to basic R&D and market subsidies seems to be the optimal policy to minimize the risk of supporting technologies that are not the best ones in the long run and, at the same time, to obtain most benefits from RE over time (Koseoglu et al. 2013, García-Olivares 2015a).

However, to be stable, a 100% renewable mix cannot be completely based on decentralized production. PV self-producers need some degree of interconnection with other producers, at a regional scale at least (Lehmann and Nowakowski 2014, Peter 2015). In addition, there are good arguments in favour of centralized stations and electric super-grids. First, industries like aluminium, iron, cement and ammonia need stable, high supplies of power at certain points. Second, since storage of electricity in batteries is currently expensive and material-intensive, PV production alone cannot avoid intermittency in production and is unable to meet nocturnal demand. Storage can be arranged more easily through reversible hydroelectric plants or CSP stations with heat storage. These systems are cheaper than batteries because water and heat are more easily stored in large quantities than electricity. Therefore, a 100% renewable mix would have to include CSP stations with heat storage and reversible hydroelectric power stations (García-Olivares et al. 2012). However, as we have seen, both hydroelectricity and CSP require specific geographical conditions and far-reaching interconnections. Smart grids could be used to integrate decentralized local production and large-scale facilities that would be required for certain energy-intensive industries. This would take best advantage of both systems: local autonomy offered by residential PV and a stable supply offered by regional interconnection with other (small and large) producers of RE (García-Olivares 2015a).

Indeed, governments and municipalities could play an important role in regulating the feeding into the grid of residential PV production, the control of the whole smart grid, the policy of self-consumption incentives, and public investment in research and development of new RE systems. However, the implementation of these regulatory measures may require the nationalization of large electric grids and the "municipalization" of local grids (García-Olivares 2015a).

Hydroelectricity and geothermal potential

Hydroelectricity has little margin for future increase because the most appropriate valleys have already been used to build hydroelectric dams. Jacobson and Delucchi (2011) estimated that only 30% of new power, up to 1 TW, could possibly be installed worldwide. Despite their limited contribution to global power, hydroelectric dams will be enormously important in a post-carbon economy as a means of energy storage (see sections below).

Large-scale geothermal power systems are currently limited to tectonically active regions, where the vertical gradient of temperature is large. These high heat-flow regions include the "Ring of Fire" in the Pacific, the area off the coasts of Indonesia, the Philippines, Japan, New Zealand, Central America and the West Coast of the USA, and rift zones such as Iceland and East Africa. These areas could benefit from major development of the technology for domestic consumption (IEA 2008, p. 393). For instance, the USA has an estimated enhanced geothermal system potential of 100 GWe, as do parts of China and India. An enhanced geothermal system is able to provide electricity and not only heat energy and can be used to provide non-intermittent electricity to the grid. In the European Union, this technology has the potential to supply 5% of demand in a future post-carbon society (Roadmap 2010). However, the choice of where to exploit this technology is controversial, because typically 20%-45% of the energy produced is used for pumping.

If in the future about 500 GWe were installed across the globe, this could contribute 4% to the total RE production of 13.5 TW.

Ocean energy

Ocean energy can be obtained by means of wave attenuators, turbines that extract power from currents and tides, and ocean thermal energy converter systems.

To illustrate the potential of marine currents, we estimate the power that could be extracted in the Strait of Gibraltar by exploiting Mediterranean Outflow Water, which is an almost permanent gravity current of dense waters that leave the Mediterranean from its lower layers, reaching maximum speeds of more than 0.73 m s^{-1} at depths of 275-325 m at the Espartel sill, 25 km from Spain and 15 km from Morocco (Calero Quesada et al. 2014). The surface layers have less energy potential due to the presence of high-frequency internal waves and periodic tidal flow reversals.

The kinetic energy of the water current can be converted into mechanical energy using turbines, which may have horizontal or vertical axes. Examples of vertical axis turbines are the Savonius, Darrieus, Gorlov and hybrid Savonius-Darrieus turbines (Alam and Iqbal 2010).

The power output of a hybrid turbine can be estimated by the following expression:

$$P = 0.5\ \rho V^3[A_s\ C_{Ps} + (A_d - A_s)\ C_{Pd}] \qquad (1)$$

where A_s is the area swept by the Savonius rotor (height Hs times diameter 2Rs, m^2), A_d is the area swept by the Darrieus rotor (m^2), C_{Ps} (C_{Pd}) is the power coefficient of the Savonius (Darrieus) rotor, and ρ is the water density (about 1030 kg m^{-3}). The expression outside the brackets in (1) corresponds to the kinetic energy flow of the current.

C_P is a function of the tip speed, λ=ωR/V, where V is the water speed, ω the angular velocity and R the radius of the rotor. C_P reaches a maximum when λ=0.8 for the Savonius and λ=5.8 for the Darrieus (C_P is 0.18 and 0.3, respectively). Therefore, λs/λd=Rs/Rd=1/5 gives good performance for both turbines. The mean kinetic energy in the layer 275-325 m depth over the Camarinal sill is 1800 W m^{-2} (Calero Quesada et al. 2014); therefore, assuming turbines with height Hd=10 m, Hs=0.3 Hd, and diameter 2R=0.8 Hd, the power obtained using Equation (1) is P=144 kW.

If we assume an 80% efficient conversion to electricity and a capacity factor CF=0.8, then to obtain 100 MWe we would need to cover about 2.1 km of the channel width with turbine installations at depths between 275 and 325 m. However, 100 MW may be supplied by an offshore wind farm with 111 turbines of 3 MW and CF=0.3. A wind farm requires lower investment and has simpler engineering and maintenance costs than an underwater installation. In addition, wind farms are scalable to the terawatt range, whereas marine turbines need to be placed in locations with intense currents (1 to 2 m s^{-1}), which are limited to very particular geographical locations, such as the Gibraltar Strait and the western parts of the oceanic gyres. Furthermore, major exploitation of planetary current systems raises concerns about potential perturbations of global climate (Hagerman 2007).

The same problem applies for large-scale exploitation of ocean thermal energy conversion (OTEC). OTEC gets its largest efficiencies (3%-4%) only in tropical waters, where temperature gradients between surface and intermediate waters are maximum. According to Nihous (2007), the available potential is 2.7 (secular scale) to 5TW (short term) if 16×10^6 m^3 s^{-1} (16 Sv) of intermediate water were pumped to surface. However, a flow of 16 Sv has the same order of magnitude as the overturning circulation, so it could disturb pelagic ecology and the global climate. As an example, intermediate waters have CO_2 concentrations of about 2300 μmol-CO_2 per kg of water, a concentration larger than at the surface (about 1950 μmol kg^{-1}). Thus, the pumped flow has the potential to add, through degassing, 253 t s^{-1} of CO_2 to the atmosphere, which is 24% of the anthropogenic CO_2 input in 2011 (see http://en.wikipedia.org/wiki/List_of_countries_by_carbon_dioxide_emissions). This degassing could be avoided with carbon capture techniques, but it would decrease the energetic efficiency of OTEC, which is already at the limit of what is implementable. Therefore, it is probable that in the near future marine turbines and OTEC will not be used at large-scale, but only at particular locations, as a local complement to the main RE resources, i.e. wind, solar and hydro.

Wave energy can be more easily extracted than marine current energy. Australia, Atlantic Europe and Chile each have about 5000 km of coast with a mean wave flow of above 50 kW m^{-1} (Hagerman 2007). Wave energy converter devices have the potential to convert about 10% of inshore flowing wave energy into electricity by using designs that simultaneously respect maritime transit and protected zones (Behrens et al. 2015). Therefore, 100% coverage of 5000 km of shoreline in any of these regions could supply 25 GW of electricity. This is one order of magnitude below the power that wind or solar energy are capable of supplying to the South American region, but it may be a valuable supply to meet demand in coastal regions. In addition, wave energy may contribute to dampening of the variability of wind power production, since wind and waves are not generally correlated except during thunderstorms.

A 100% renewable mix for a post-carbon economy

In conclusion, a 100% RE mix of 12 TW of mean power could be provided by combining PV, CSP, wind, hydroelectricity, small contributions of geothermal and marine energy, and occasional back-ups from stations fired by gas and hydrogen obtained from renewable sources. Perhaps 1 TW could be obtained from roof panels, 1 TW from utility-scale PV, 1 TW from hydroelectricity, and 9 TW from CSP and wind energy.

Even in a scenario of low shelf and continent occupation, wind power alone is capable of supplying almost the full 9 TW total, and CSP alone is also capable of supplying this power provided subtropical deserts are integrated into continental high-voltage direct current grids (García-Olivares et al. 2012). The concrete share of the two technologies in a future post-carbon economy will depend on the evolution of their respective costs and on political decisions. However, a minimum share of CSP will be necessary to grant safe management of RE power intermittency, as we will discuss in the following section.

MITIGATION OF INTERMITTENCY

Among the most delicate issues regarding a 100% RE mix are the mitigation of intermittency in supply and the fitting of supply to demand. Electricity supplied by a combination of wind and solar power is less intermittent than that supplied by one RE alone (Roadmap 2010). In addition, the production of CSP with storage from subtropical deserts is not intermittent on the scale of hours to days, and could be used as a base load for the grid, with minor contributions from enhanced geothermal systems. Given that the base load is roughly 75% of the total mean power in industrialized economies, about 9 TW would have to be produced with CSP if it alone was going to provide the base load of a 12 TW economy. The grid operator could reduce this high contribution from CSP if the base load were provided by a combination of all renewables on average days (as in the figure on page 63 of Jacobson and Delucchi 2009) and by CSP alone on days of very low wind and PV production. Also, future developments of electricity storage systems will probably add a rising fraction of power usable as base load. Frequency regulation (scale from seconds to hours) is the most sensitive part of the grid stability. In a 100% RE grid it could be provided by ramping up/down hydroelectricity, stored CSP or pumped hydro storage; ramping down other RE generators and storing the electricity in heat, cold or hydrogen instead of curtailing (Jacobson et al. 2015).

Nevertheless, power supplied by renewable sources may be relatively intermittent during periods of high cloudiness or high pressure, which normally last 2-3 days (MIT 2015, p. 6). This 3-day variability may be mitigated by (i) sufficient geographical interconnection (Czisch 2008); (ii) use of hydroelectric power to smooth out supply (Czisch and Giebel 2007, Czisch 2008); (iii) using reversible electric vehicle recharging as grid storage (Kempton and Tomic 2005); (iv) using electric storage systems such as water pumping, air compression, batteries, and hydrogen production and storage; (v) using smart demand-response management and weather prediction to better match inflexible loads to the power supply (Delucchi and Jacobson 2011); and (vi) installing fast-response power plants (of hydrogen or natural gas) as last resort back-ups.

The first two methods alone are able to solve the problem for/in many regions. For example, the total hydropower storage capacity of the European grid system is more than 180 TWh (Eurelectric 2013). If 30% additional hydro capacity were developed in a post-carbon economy, we would have 234 TWh, which would be equivalent to six days of future consumption of energy in Europe (1.68 TW). Moreover, a complete fall of RE supply is practically impossible if the grid interconnection has a continental size. Czisch (2008) shows how monthly variability can be completely matched in a European grid that also includes northern Russia, Kazakhstan, southern Morocco and Mauritania. Dedicating hydro plants to the prevention of power shortages from other RE production would alter their routine operation and diminish their steady power generation, but could almost completely solve the intermittency problem of an RE mix in the EU. In a future post-carbon economy this use of hydroelectric power will be the norm, unless the cost of other energy storage technologies decreases substantially. The optimal way to combine CSP, interconnection and hydro storage depends on many geographical details, but Czisch (2008) shows that the problem can be essentially solved by interconnection, sufficient CSP, and backup supplied by hydro and biomass stations.

ENERGY RETURN OF A 100% RENEWABLE MIX

The EROEI is defined as:

$$\mathrm{EROEI} = E_{out} / E_{in} \tag{2}$$

where E_{out} is the energy that an energy technology (e.g. a PV panel or all the PV panels of a country) provides over the whole useful life of the technology, and E_{in} is the energy input required during the life cycle of the technology. The effective EROEI of a complete economy can also be obtained by averaging the EROEI of its energy technologies. The effective EROEI of an economy should be high enough to sustain economic activity different to the energy production itself. Some authors consider 10 as the minimum EROEI value that any economy should have to avoid the risk of erosion of important social activities (Heinberg 2009).

When the EROEI of PV is calculated, the numerator of (2) is electrical energy provided by the PV industry, but the denominator of (2) is mostly energy invested in the making of the panels, which is essentially energy from fossil fuels. Another definition widely used is the ‘EROEI primary energy equivalent’, $\mathrm{EROEI}_{PE\text{-}eq}$. This evaluates expression (2) using for the numerator the net energy output over the PV system’s lifetime but expressed in terms of its ‘primary energy equivalent’, and not directly as electricity. The conversion is normally done on the basis of the ‘life cycle energy conversion efficiency’ of the current electric grid (η_{grid}), i.e.

$$E_{OUT\text{-}PE\text{-}eq} = E_{OUT}/\eta_{grid}$$

where, for instance, η_{grid}=0.29 for the USA, and 0.31 for the EU-27 (Raugei et al. 2012).

The resulting expression is useful for estimating how much primary energy is virtually ‘returned’ to society (i.e. preserved for alternative uses) per unit of primary energy invested in the technology, given the composition of the current electric grid. But it is also useful for estimating the EROEI of renewable sources that produce electricity as output (i.e. PV, CSP, wind and hydro) in a future post-carbon economy in which essentially all the processes would consume electricity. Indeed, the resulting expression is:

$$\mathrm{EROEI}_{PE\text{-}eq} = E_{out} / \eta_{grid}\, E_{in}$$

and the denominator is approximately the energy E_{in}^{el} that would have been used if the input energy were electrical energy instead of fossil fuel energy:

$$\mathrm{EROEI}_{PE\text{-}eq} \cong E_{out} / E_{in}^{el} \tag{3}$$

where $E_{in}^{el}=\eta E_{in}$, with η being the future conversion efficiency of thermal energy to electricity, which is assumed to be close to the present one (η_{grid}).

A strong disagreement exists between different groups about the EROEI of the PV energy. According to Carbajales-Dale et al. (2015), it ranges between an $EROEI_{PE\text{-}eq}$ (EROEI primary energy equivalent) of 19 for a mono or multi-crystalline silicon PV (the Fthenakis group at Brookhaven) and an EROEI of 2.45 (Prieto and Hall 2013) for the Spanish PV industry. The analysis by Prieto and Hall (2013) is very detailed and uses data from the Spanish PV industry. The value obtained by them for the EROEI of Spanish PV must be considered a realistic estimation of the figures that can be expected in present PV installations at national scale.

The argument of Prieto and Hall for using EROEI and not $EROEI_{PE\text{-}eq}$ is that "if we would pretend to use electricity from renewables to replace the fossil fuels used for these global activities, likely through an energy carrier like the eternal hydrogen promise, the pretended multiplication factor used by Carbajales et al. (2015), would immediately operate in the reverse form and become a division factor, probably in the order of 3, with respect to the direct use of fossil fuels of today. That is why we did not employ this "correction factor" used by Carbajales et al. (2015)" (http://energyskeptic.com/2015/tilting-at-windmills-spains-solar-pv/).

This is a convincing argument if PV installations were to be used to produce the fuels that the present economy requires (a fleet of 1000 million vehicles with fuel hydrogen cells, fuels for industrial heating, combustion engine-driven industrial machines, and so on). However, it is not a convincing argument if we are studying a future PV system in an electrified post-carbon economy in which hydrogen use is small relative to direct electricity use.

If the fraction (α) of electricity that must be used for hydrogen fuel production is known, the following expression can be used to calculate the effective EROEI of a post-carbon economy ($EROEI_{PC}$):

$$EROEI_{PC} = [(1\text{-}\alpha)\,(f_W/E_W + f_{PV}/E_{PV} + f_{CSP}/E_{CSP} + f_H/E_H) + 2.1\,\alpha\,(f_W/E_W + f_{PV}/E_{PV} + f_{CSP}/E_{CSP} + f_H/E_H) + f_B/E_B]^{-1} \quad (4)$$

where f refers to the share of the renewable sources in the mix (W, wind; PV, photovoltaics; CSP, concentrating solar power; H, hydroelectric; B, biomass), E refers to the EROEI of the renewable sources, and α is the fraction of generated electricity that is used for hydrogen production. The factor 2.1 is the ratio between the electricity required for producing and transporting a given mass of hydrogen and the low heating value content of that mass (Bossel 2005).

$EROEI_{PE\text{-}eq}$ is used instead of EROEI in (4) given that the effect of hydrogen production is explicitly accounted for. The $EROEI_{PE\text{-}eq}$ of PV in Spain would be 8 if we transformed the corresponding value of the EROEI obtained by Prieto and Hall (2013). Given that this figure is in the lower range of published estimations, let us take it as a conservative value for EROEI of PV production in a post-carbon society.

Let us assume that 4 TW will be supplied with wind energy, 7 TW with solar energy (1 TW from home PV, 1 TW from ground PV, and 5 TW from CSP) and 1 TW with hydroelectricity. Currently installed turbines have an EROEI of about 20 and CSP stations of about 18 if salts for energy storage have to be synthesized (García-Olivares et al. 2012); hydroelectric EROEI is about 84 (Hall et al. 2014), and solar PV EROEI is taken as 8. In 2005, 1.47 TW of biomass was used for energy purposes. We assume that this consumption will remain in a future post-carbon society, so the total renewable power production (including biomass) will be 13.5 TW and the share of biomass in the renewable mix will be 10.9%. Gagnon reports an EROEI of 27 for biomass wastes, but this figure decreases to 5 if biomass has to be hauled 20 km. We will take an EROEI of 20 as an intermediate figure for biomass.

García-Olivares (2015b) estimated the electricity necessary to produce hydrogen in a post-carbon economy able to supply similar services to those of the 2005 economy under different scenarios of transport reorganization. According to that study, a post-carbon economy will require hydrogen for chemical reduction of iron, copper, tin and nickel, for fueling fuel cells of ships and specialty vehicles, and for aviation. That study also concludes that maintaining the same activity level in the aviation sector would require a disproportionate waste of electricity; that use of fuel cells should be limited to 10% of the present commercial fleet to avoid the deployment of the platinum-palladium reserves; and that ammonia could be produced either from hydrogen or from renewable biogas or be completely avoided by moving to a fully organic agriculture. If we use the scenario with zero hydrogen-based production of ammonia, 10% of the commercial fleet being powered by hydrogen fuel cells, and a reduction in aviation activity to 50% of its 2005 level, then 1.3 TW of electricity would be required in the post-carbon economy for hydrogen production. This is equivalent to α=0.11 in (4). Using this parameter and those mentioned above, the value obtained from (4) is $EROEI_{PC}$=15.

We can compare this value with the effective EROEI of the present fossil fuel economy. In this case, an expression equivalent to (4) is the following:

$$EROEI_{FF} = [f_O/E_O + f_C/E_C + f_G/E_G + f_H/E_H + f_N/E_N + f_R/E_R + f_B/E_B]^{-1} \quad (5)$$

where f refers to the share of the fossil fuel sources (O, oil; C, coal; G, gas; H, hydro; N, nuclear; R, new renewables; B, biomass).

Table 4 shows the primary energy produced from different sources in 2005 (Grubler et al. 2012), their share in the mix, and their EROEI estimated by different sources. Using this table and expression (5), the EROEI of the present fossil fuel economy can be estimated as $EROEI_{FF}$=23. Thus, the EROEI of a future 100% renewable mix would be about eight units lower than the present one. Approximately 37.5% of that descent (3 units) would be caused by the abandonment of coal, which has a relatively high EROEI (46), another 37.5% (3 units) would be caused by the introduction of the low EROEI PV systems and 25% (2 units) would

Table 4. – Primary energy produced from different sources in 2005 (Grubler et al. 2012), their share in the mix and their EROEI estimated by different sources: a, Gagnon et al. (2009); b, Hall et al. 2014; c, based on Hall et al. (2014) and Vant-Hull (1985); d, based on Gagnon (2008).

Fuel	Energy (EJ)	Share (%)	EROEI
Oil	167.4	33.8	18.5[a]
Coal	122.2	24.6	46.[b]
Gas	99.0	20.	18.5[a]
Hydro	30.1	6.1	84.[b]
Nuclear	28.5	5.7	14.[b]
New renewables	2.3	0.5	19.[c]
Biomass	46.3	9.3	20.[d]

derive from the future hydrogen production. Given that the EROEI value used for PV was conservative and that learning curves of RE systems are currently at their beginning, the EROEI of a future RE mix would probably increase a long time after its implementation.

The net useful energy, E_u, available for supplying to end uses is related to EROEI through the following expression:

$$E_u = E_p\left(1-\frac{1}{\text{EROEI}}\right) \qquad (6)$$

According to (6), the present economy uses 96% of primary energy outside the energy sector, and in a future RE mix the figure would decrease to 93%.

EROEI values above 10 (net energy above 90%) are considered sufficient to sustain a complex society (Heinberg 2009), so a 100% renewable post-carbon society would be capable, in principle, of sustaining an industrial developed economy provided the industrial processes based on fossil fuels were replaced by electric processes.

DISCUSSION AND CONCLUSION

A future post-carbon economy is a feasible sustainable solution to the present challenges of energy security and rising environmental impacts. Such a future economy should be based on a mix of decentralized and centralized renewable sources. Some studies have warned of the necessity and difficulty of the transition to such a society, and others even argue that such a transition is impossible due to limitations of global RE potential. The work presented here acknowledges the political and economic difficulty of carrying out the transition, but shows that it will probably not be limited by the RE potential, which is sufficient to supply 12 TWe globally if continental shorelines and highly insolated deserts are exploited with currently proven technologies. The present analysis can be considered as a piece of assessment based on “foresight knowledge” in the meaning of Frame and Brown (2008), who developed the concept of “post-normal science” (Funtowicz and Ravetz 1993). According to those authors, foresight knowledge has a series of attributes, namely that (i) it is non-verifiable (e.g. in a predictive sense) because it does not give a representation of an empirical reality, (ii) it contains a high degree of uncertainty and complexity, (iii) it thematizes a coherent vision of the future that includes an “anticipation of the unknown”, (iv) it contains an action-oriented perspective (unlike normal science, which lacks such a perspective), (v) it shares a hermeneutical dimension with the social sciences and the humanities whereby knowledge is subject to continuous interpretation (e.g. alternative visions of “the future”), (vi) it is more than merely future-oriented but attempts to combine normative objectives with socio-economic feasibility and scientific plausibility, and (vii) it is trans-disciplinary in its approach.

A future post-carbon society would be mainly based on wind, onshore and offshore, CSP, residential PV, utility-scale PV and hydroelectricity. To obtain 12 TWe, 10% of continental shelves would have to be colonized with offshore turbines down to 225 m depth, 5% of all the continents would be populated with onshore turbines, 5% of the main insolated deserts would be used for CSP farms, 12.5% of the populated space would have roof PV panels installed, and an area similar to that occupied by the populated space would support utility-scale PV farms. Other combinations of onshore wind, offshore wind, CSP and PV are possible to achieve this global power production.

PV energy was considered by some authors to be incapable of playing a large role in a future 100% RE society because it was based on rare materials and has very low EROEI values. However, recent developments avoid the use of silver in the metallization of crystalline silicon cells, and so allow the scaling-up of PV power to the terawatt range. The probable wide deployment of residential PV panels will enhance residential autonomy and people’s empowerment and may take societies closer to an “energy democracy” (Scheer 2012) with enhanced access to energy for common people. This can be especially important for developing countries, where the access of domestic shareholders to a minimum energy consumption can make the difference between misery and poverty. However, to be stable, decentralized PV production should be integrated with centralized production by means of smart grids at regional and even continental scales. This would require international cooperation between, for instance: Europe, Maghreb and Russia; China and Australia; the South American countries; and the African countries. In particular, CSP in deserts may make subtropical countries 100% energetically self-sufficient.

Apart from desirability and availability, viability is another crucial factor for a successful implementation of a new energy mix (Giampietro et al. 2014). Viability is related to constraints imposed by the internal metabolism of an economy, e.g. labour force, resources and net energy necessary for homeholders, government and service sectors, or requirements of enough space and water for agriculture. In addition, the new RE mix should be compatible with the number of hours per capita per year available in the paid work sector, a figure normally about 1000, where 600-700 hours are required by the service and government sectors (Giampietro et al. 2014).

This subject would require a detailed study, but the requirement of space and water of a 100% RE mix are apparently viable (Jacobson and Delucchy 2011, García-Olivares et al. 2012). An RE mix will probably not increase the present demand for water and space provided that biofuels production is strictly limited and based on agriculture waste. As an example, CSP may use fan cooling in arid regions and it practically avoids the use of water, which cannot be said of present energy mining. On the other hand, net energy provided by an RE mix to the end uses will be only 3% lower than in the present economy according to the approximate EROEI estimations laid out above. And regarding paid work, labour productivity of wind and CSP systems are as high as in the rest of industry, which will probably not affect their viability.

The EROEI of biofuels has been reported to be currently very low, though with great potential for improvement (Hall et al. 2011). A limited production of them could be necessary to replace fossil fuels in future aviation engines. However, land grabbing for biofuels production has been reported in Africa and other regions (Matondi et al. 2011) and it could lead to competition with food production. To avoid the consequent risks, governments should further regulate biofuels production so that it does not affect food security.

The energy consumption of a future 100% renewable economy seems to have a cap of about 12 TW due to limited copper reserves. Although reserves tend to increase with time, responding to new demand and rising prices, the increase cannot be expected to be limitless. If the estimated reserve base for copper (10^9 t) is assumed to be the future reserve in the next 50 years, 33-38% of copper reserves would still have to be kept for the deployment of the new electric economy. Therefore, the continuation of the customary exponential growth of energy would soon be impeded by the rising scarcity of this metal.

A way to relax this limitation is to replace copper with aluminium in electric generators, motors and wires. Most of the consumption of copper in a post-carbon economy will be for windings in generators and electric motors (García-Olivares et al. 2012). Squirrel-cage motors frequently use aluminium instead of copper for the conductive bars, though they are built for low and medium power (a few kW) and outside the range required by a power generator (MW). Another possible development is the use of graphene and high-temperature superconductors in electric generators, motors and wires. The degree of savings in terms of copper usage that these developments will produce is difficult to assess. We cannot discard the possibility that high-power motors and generators will be developed in the future that employ aluminium, graphene or high-temperature superconductors instead of copper. However, caution prevents us from counting on them as a future solution and, even in the best case, technological innovations take 40-50 years to expand throughout the economy.

Lithium will also be used massively in the batteries of electric vehicles and may become scarce. A way to relax future limitations of lithium is to diversify the use of metals in batteries. If the present world fleet of 10^9 vehicles is to be transformed into electric vehicles, 8 Mt of lithium will be required, which is 59% of present reserves (USGS 2015, Lithium). However, the entire vehicle fleet does not have to be based on lithium batteries, since nickel batteries Na-$NiCl_2$ (Zebra) are proven technologies in the electric vehicle market. If all batteries were based on nickel, 81% of nickel reserves would have to be used. But if 50% of electric vehicles were based on each of these two batteries, only 30% and 41% of reserves of Li and Ni would be used, respectively. This would also require production rates of Li 5-10 times larger than the present ones (García-Olivares et al. 2012). Currently, Li is mainly produced by a few countries (Australia, Chile, Chine, Argentina, Zimbabwe, Portugal and Brazil). The rising price of Li could stimulate these countries to increase their production, but it may cause environmental justice problems because Li extraction is difficult and has a strong environmental impact. It is not clear whether a system of global exportation of Li would be desirable for producer countries in the future. If the answer to this question is "no", the vehicles fleet would probably have to be reduced in a future RE economy.

A much more safe way to save copper, lithium and nickel would be to replace private vehicles with trains. About 30% of the copper needed for a 100% electric economy goes to vehicle electrification, and only 3.3% to electrification of the rail transport system (García-Olivares et al. 2012). However, electric trains are much more efficient than private cars for transport of people. One electric train of 1160 kW such as the S-448 of RENFE in Spain (http://www.renfe.com/viajeros/nuestros_trenes/md448_ficha.html) is able to transport 237 seated passengers at 160 km h^{-1} between two cities. A car, on the other hand, normally transports 1-2 persons with a power of, typically, 60 kW in the case of electric cars. Thus, an intercity train transports eight times more seated passengers per MW than a car (204 persons/MW vs 25 persons/MW). The ratio is larger if passengers are standing, as in urban trains.

These developments may relax the above-mentioned limitations but it is implausible that they will allow the exponential growth in the use of metals to continue for long. Sooner or later, a 100% RE economy with a level of energy supply in the range of 12 TWe will need to adapt to a situation of stationary energy consumption.

In a future 100% RE economy the emphasis on adapting power supply to demand will have to be relaxed and, instead, emphasis will be on intelligent management of demand to adapt it to natural cycles of RE production. The unpredictable variability of RE production may be balanced with sufficient use of CSP, hydro storage and regional grid interconnection. Marine energy will also contribute towards stabilizing RE intermittency, though it will only be important locally. OTEC has been claimed to have a global potential of a few TW, but it would imply the pumping to the surface of 254 t s^{-1} of CO_2, which is 20-24% of anthropogenic emissions. Therefore, this technology will probably only be important for tropical islands. Small contributions of geothermal and wave energy will probably be important at specific geographical places, while energy from marine currents is not expected to be competitive with other energy sources. In contrast, wind energy of marine origin will be one of the main contributions to the future mix, with up to 1 TW of global production. A similar contribution (1 TW) may come from hydro, residential PV and utility-scale PV.

The EROEI of some RE technologies has been reported to be small, and this raises some doubts on the capability of a future 100% renewable power system to provide a sufficiently effective EROEI. However, an economy with the mix that we have discussed above would have an effective EROEI of about 15. This is lower than the EROEI value estimated for the present fossil fuel economy (23) but it should allow us, in principle, to sustain a future stationary developed economy. However, the energy transition should be made efficiently since inefficiencies could take the EROEI value close to the limit of 10 that some authors consider incompatible with a complex economy.

The best way to adapt our economy for stationary power production is not evident. It should be discussed and planned in advance, since the 'business as usual' economic practice is not able to provide the enormous investment and substitution that a stationary electrified economy will require.

ACKNOWLEDGEMENTS

This Work has been partially supported by projects "TIC-MOC", ref. No. CTM2011-28867 and "VA-DE-RETRO", ref. No. CTM2014-56987-P, financed by the Ministerio de Economía y Competitividad, from the Spanish National Research Programme.

REFERENCES

Adams A.S., Keith D.W. 2013. Are global wind power resource estimates overstated? Environ. Res. Lett. 8: 015021. http://dx.doi.org/10.1088/1748-9326/8/1/015021

Alam J., Iqbal M.T. 2010. A Low Cut-In Speed Marine Current Turbine. J. Ocean Technol. 5: 49-61.

Amante C., Eakins B.W. 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources And Analysis. National Oceanic And Atmospheric Administration. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center Marine Geology and Geophysics Division. Boulder, Colorado. http://www.gebco.net/data_and_products/gridded_bathymetry_data/

Barzantny K., Achner S., Vomberg S. 2009. Klimachutz: Plan B 2050: Energiekonzept für Deutschland. Greenpeace, Hamburg.

Behrens S., Hayward J.A., Woodman S.C., et al. 2015. Wave energy for Australia's National Electricity Market. Renewable Energy 81: 685-693. http://dx.doi.org/10.1016/j.renene.2015.03.076

Bossel U. 2005. On the Way to a Sustainable Energy Future, Proceed.27th Intern. Telecom. Conf., Sept. 2005, 659-668. Berlin. http://dx.doi.org/10.1109/INTLEC.2005.335178

Calaf M., Meneveau C., Meyers J. 2010. Large eddy simulation study of fully developed wind-turbine array boundary layers. Phys. Fluids 22: 015110. http://dx.doi.org/10.1063/1.3291077

Calero Quesada M.C., García-Lafuente J., Sánchez Garrido J.C., et al. 2014. Energy of marine currents in the Strait of Gibraltar and its potential as a renewable energy resource. Renew. Sustain. Energy Rev. 34: 98-109 http://dx.doi.org/10.1016/j.rser.2014.02.038

Carbajales-Dale M., Raugei M., Fthenakis V., et al. 2015. Energy return on investment (EROI) of solar PV: An attempt at reconciliation [Point of View]. Proceed. IEEE 103(7): 995-999. http://dx.doi.org/10.1109/jproc.2015.2438471

Chapman I. 2013. The end of peak oil? Why this topic is still relevant despite recent denials. Energy Policy 64: 93-101. http://dx.doi.org/10.1016/j.enpol.2013.05.010

Creutzig F., Goldschmidt J.C., Lehmann P., et al. 2014. Catching two European birds with one renewable stone: Mitigating climate change and Eurozone crisis by an energy transition. Renew. Sustain. Energy Rev. 38: 1015-1028. http://dx.doi.org/10.1016/j.rser.2014.07.028

Czisch G. 2008. Totally Renewable Electricity Supply: a European/Trans-European Example. Medenergie 27: 1-19.

Czisch G., Giebel G. 2007. Realisable Scenarios for a Future Electricity Supply Based on 100% Renewable Energies. Proceed. Risø Intern. Energy Conf. Energy Sol. Sustain. Develop.: 186-195. Risø National Laboratory. Kopenhagen, Denmark, May 2007.

De Castro C., Mediavilla M., Miguel L.J., et al. 2011. Global wind power potential: Physical and technological limits. Energy Policy 39: 6677-6682. http://dx.doi.org/10.1016/j.enpol.2011.06.027

De Castro C., Mediavilla M., Miguel L. J., et al. 2013. Global solar electric potential: A review of their technical and sustainable limits. Renew. Sustain. Energy Rev. 28: 824-835. http://dx.doi.org/10.1016/j.rser.2013.08.040

Delucchi M.A., Jacobson M.Z. 2011. Providing all global energy with wind, water, and solar power, part II: reliability, system and transmission costs, and policies. Energy Policy 39 (3): 1170-1190. http://dx.doi.org/10.1016/j.enpol.2010.11.045

Eurelectric 2013. Hydropower for a sustainable Europe. Eurelectric Fact Sheets. Brussels. http://www.eurelectric.org/hydro-factsheets

Fouquet R. 2010. The slow search for solutions: Lessons from historical energy transitions by Sector and service. Energy Policy 38: 6586-6596. http://dx.doi.org/10.1016/j.enpol.2010.06.029

Frame B., Brown J. 2008. Developing post-normal technologies for sustainability. Ecological Economics 65: 225-241. http://dx.doi.org/10.1016/j.ecolecon.2007.11.010

Funtowicz S., Ravetz J.R. 1993. Science for the Post-Normal Age. Futures 25: 735-755. http://dx.doi.org/10.1016/0016-3287(93)90022-L

Gagnon L. 2008. Civilisation and energy payback. Energy Policy 36: 3317-3322. http://dx.doi.org/10.1016/j.enpol.2008.05.012

Gagnon N., Hall C.A.S., Brinker L. 2009. A preliminary investigation of energy return on energy investment for global oil and gas production. Energies 2: 490-503. http://dx.doi.org/10.3390/en20300490

García-Olivares A. 2015a. Substituting silver in solar photovoltaics is feasible and allows for decentralization in smart regional grids. Environ. Innov. Societ. Transitions 17: 15-21. http://dx.doi.org/10.1016/j.eist.2015.05.004

García-Olivares A. 2015b. Substitutability of electricity and renewable materials for fossil fuels in a post-carbon economy. Energies 8(12): 13308-13343. http://dx.doi.org/10.3390/en81212371

García-Olivares A., Ballabrera-Poy J. 2014. Energy and mineral peaks, and a future steady state economy. Technol. Forecast. Soc. Change 90: 587-598. http://dx.doi.org/10.1016/j.techfore.2014.02.013

García-Olivares A., Turiel A. 2013. The Second Half of the Fossil Fuel Age: Environmental Externalities, Net Energy And Energy Security Concerns. In: Kumar R. (ed.), Fossil Fuels, Sources, Environmental Concerns and Waste Management Practices. Ed. Nova, New York, pp. 271-290.

García-Olivares A., Ballabrera J., García-Ladona E., et al. 2012. A global renewable mix with proven technologies and common materials. Energy Policy 41: 561-574. http://dx.doi.org/10.1016/j.enpol.2011.11.018

Giampietro M., Aspinall R.J., Ramos-Martin J., et al. (eds). 2014. Resource Accounting for Sustainability Assessment: The Nexus Between Energy, Food, Water and Land Use. Routledge, New York.

Grandell L., Thorenz A. 2014. Silver supply risk analysis for the solar sector. Renewable Energy 69: 157-165. http://dx.doi.org/10.1016/j.renene.2014.03.032

Grandy W.T. Jr. 2008. Entropy and the Time Evolution of Macroscopic Systems. Oxford Univ. Press, Oxford. http://dx.doi.org/10.1093/acprof:oso/9780199546176.001.0001

Grubler A., Johansson T.B., Mundaca L., et al. 2012: Chapter 1 - Energy Primer. In: Global Energy Assessment - Toward a Sustainable Future, pp. 99-150. Cambridge Univ. Press, Cambridge

http://dx.doi.org/10.1017/CBO9780511793677.007
Hagerman G. 2007. Energy from Tidal, River, and Ocean Currents and from Ocean Waves. EESI Briefing on "The Role of Advanced Hydropower and Ocean Energy in Upcoming Energy Legislation", Washington DC.
Hall C.A.S., Dale B.E., Pimentel D. 2011. Seeking to Understand the Reasons for Different Energy Return on Investment (EROI) Estimates for Biofuels. Sustainability 3: 2413-2432. http://dx.doi.org/10.3390/su3122413
Hall C.S., Lambert J.G., Balogh S.B. 2014. EROI of different fuels and the implications for society. Energy Policy 64: 141–152. http://dx.doi.org/10.1016/j.enpol.2013.05.049
Heinberg R. 2009. Searching for a Miracle. Post Carbon Institute, False Solution Series #4.
Heinberg R. 2014. The end of growth. New Society Publishers, Vancouver.
IEA. 2008. Energy Technology Perspectives in Support of the G8 Plan of Action. Scenarios and Strategies to 2050. OECD / IEA, Head of Communication and Information Office, Paris, France.
IPCC. 2011. Special Report on Renewable Energy Sources and Climate Change Mitigation. http://www.ipcc-wg3.de/
Jacobson M.Z., Delucchi M.A. 2011. Providing all global energy with wind, water, and solar power, part I: technologies, energy resources, quantities and areas of infrastructure, and materials. Energy Policy 39(3): 1154-1169. http://dx.doi.org/10.1016/j.enpol.2010.11.040
Jacobson M. Z., Delucchi M.A., Bazouin G., et al. 2015. 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. Energ. Environ. Sci. 8: 2093-2117. http://dx.doi.org/10.1039/C5EE01283J
Kawajiri K., Oozeki T., Genchi Y. 2011. Effect of Temperature on PV Potential in the World. Environ. Sci. Technol. 45: 9030-9035. http://dx.doi.org/10.1021/es200635x
Kempton W., Tomic J. 2005. Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy. J. Power Sources 144: 280-294 http://dx.doi.org/10.1016/j.jpowsour.2004.12.022
Koseoglu N.M., van den Bergh J.C.J.M., Lacerda J.S. 2013. Allocating subsidies to R&D or to market applications of renewable energy? Balance and geographical relevance. Energy Sustain. Dev. 17: 536-545. http://dx.doi.org/10.1016/j.esd.2013.08.002
La Gennusa M., Lascari G., Rizzo G., et al. 2011. A model for predicting the potential diffusion of solar energy systems in complex urban environments. Energy Policy 39: 5335-5343. http://www.sciencedirect.com/science/article/pii/S0301421511004174
Leggett L.M., Ball D.A. 2012. The implication for climate change and peak fossil fuel of the continuation of the current trend in wind and solar energy production. Energy Policy 41: 610-617. http://dx.doi.org/10.1016/j.enpol.2011.11.022
Lehmann H., Nowakowski M. 2014. Archetypes of a 100% renewable energies power supply. Energy Procedia 57: 1077-1085. http://dx.doi.org/10.1016/j.egypro.2014.10.093
Matondi P.B., Havnevik K., Beyene A. 2011. Biofuels, land grabbing and food security in Africa. Zed Books, London, 248 pp.
Mearns E. 2011. Peak Oil—Now or Later? A Response to Daniel Yergin, The Oil Drum http://www.theoildrum.com/node/8391
Miller L.M., Gaus F., Kleidon A. 2011. Estimating maximum global land surface wind power extractability and associated climatic consequences. Earth Syst. Dynam., 2: 1-12. http://dx.doi.org/10.5194/esd-2-1-2011
MIT 2015. Richard Schmalensee et al. The Future of Solar Energy: An Interdisciplinary MIT Study. Massachusetts Institute of Technology.
Murray J., King D. 2012. Oil's tipping point has passed, Nature 481: 433-435. http://dx.doi.org/10.1038/481433a
Nihous G.C. 2007. A preliminary assessment of ocean thermal energy conversion resources. Transactions of the ASME 129, 10-17 March 2007. http://dx.doi.org/10.1115/1.2424965
Niven R.K. 2009. Jaynes' MaxEnt, Steady State Flow Systems and the Maximum Entropy Production Principle. AIP Conf. Proc. 1193, 397. Conference date: 5-10 July 2009 http://dx.doi.org/10.1063/1.3275639
Pascale S., Gregory J.M., Ambaum M.H.P., et al. 2012. A parametric sensitivity study of entropy production and kinetic energy dissipation using the FAMOUS AOGCM. Clim. Dyn. 38: 1211-1227. http://dx.doi.org/10.1007/s00382-011-0996-2
Peter S. 2015. Modellierung einer vollständig auf erneuerbaren Energien basierenden Stromerzeugung im Jahr 2050 in autarken, dezentralen Strukturen. Dessau-Roßlau: Umweltbundesamt (in German).
Pleßmann G., Erdmann M., Hlusiak M., et al. 2014. Global energy storage demand for a 100% renewable electricity supply. Energy Procedia 46: 22-31. http://dx.doi.org/10.1016/j.egypro.2014.01.154
Prieto P., Hall C.A.S. 2013. Spain's Photovoltaic Revolution. The Energy Return on Investment, Springer, Berlin. http://dx.doi.org/10.1007/978-1-4419-9437-0
Raugei M., Fullana-i-Palmer P., Fthenakis V. 2012. The energy return on energy investment (EROI) of photovoltaics: Methodology and comparisons with fossil fuel life cycles. Energy Policy 45: 576–582. http://dx.doi.org/10.1016/j.enpol.2012.03.008
Roadmap. 2010. Roadmap 2050 - Practical guide to a prosperous, low-carbon Europe. European Climate Foundation. http://www.roadmap2050.eu/
Scheer H. 2012. The energy imperative. 100 per cent renewable now. Earthscan, London.
Schneider A., Friedl M.A., Potere D. 2009. A new map of global urban extent from MODIS satellite data. Environ. Res. Lett. 4: 1-11. http://dx.doi.org/10.1088/1748-9326/4/4/044003
Singer S. (ed.) 2011. The Energy Report: 100% Renewable Energy by 2050. World Wide Foundation. https://www.wwf.or.jp/activities/lib/pdf_climate/green-energy/WWF_EnergyVisionReport.pdf
Trieb F. 2006. Trans-Mediterranean Interconnection for Concentrating Solar Power. TRANS-CSP Study Report, DESERTEC Project. http:// www.dlr.de/tt/trans-cspS
Ummel K. 2010. Concentrating Solar Power in China and India: A Spatial Analysis of Technical Potential and the Cost of Deployment. Working Paper 210, July 2010. Center for Global Development. Washington DC.
USGS. 2015. US Geological Survey. Commodity Statistics and Information. http://minerals.usgs.gov/minerals/pubs/commodity/
Vant-Hull L. 1985. Solar thermal power-generation—the solar tower, progress toward commercialization. Nat. Resour. J. 25: 1099-1117.
Ziegler H. 1983. An Introduction to Thermomechanics. North-Holland publishing company, Amsterdam, The Netherlands, 370 pp.