Renewable Energy 116 (2018) 258–271

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Renewable transitions and the net energy from oil liquids: A scenarios study

Jordi Solé*, Antonio García-Olivares, Antonio Turiel, Joaquim Ballabrera-Poy

Institut de Ciències del Mar (CSIC), Passeig marítim de la Barceloneta 37-49, 08003, Barcelona, Spain

ARTICLE INFO

Article history:
Received 24 September 2016
Received in revised form
1 June 2017
Accepted 10 September 2017
Available online 13 September 2017

Keywords:
EROI
Energy transition
Renewable energy
Fossil fuels
Oil liquids
Net energy
URR (Ultimate Recoverable Resources)

ABSTRACT

We use the concept of Energy Return On energy Invested (EROI) to calculate the amount of the available net energy that can be reasonably expected from World oil liquids during the next decades (till 2040). Our results indicate a decline in the available oil liquids net energy from 2015 to 2040. Such net energy evaluation is used as a starting point to discuss the feasibility of a Renewable Transition (RT). To evaluate the maximum rate of Renewable Energy Sources (RES) development for the RT, we assume that, by 2040, the RES will achieve a power of 11 TW (10^{12} Watt). In this case, by 2040, between 10 and 20% of net energy from liquid hydrocarbons will be required. Taking into account the oil liquids net energy decay, we calculate the minimum annual rate of RES deployment to compensate it in different scenarios. Our study shows that if we aim at keeping an increase of 3% of net energy per annum, an 8% annual rate of RES deployment is required. Such results point out the urgent necessity of a determined policy at different levels (regional, national and international) favoring the RT implementation in the next decades.

1. Introduction

The necessity of a global transition to sources of renewable energy production, or Renewable Transition (RT), has now a relevant place in the political agenda as illustrated by the recent commitment of G7 countries and the EU for a future sustainable energy security supply (EC news, may 2015) [1]. But even before this commitment, the last years have seen a very active debate about the need, and feasibility, of the RT in energy policy research. Currently, in climate forums, there is a general agreement that, in order to avoid the climate change most damaging effects and keep the global temperature under manageable limits, the RT must not be delayed anymore. In other words, although some scenarios consider the possibility to extract enough fossil fuels to keep the economic growth and maintain the system in the same way than today [2], the environmental and climatic impacts of keep increasing the GHG emissions would produce in the future disastrous consequences.

On the other hand, the feasibility and pace of the RT has been also a subject of intense debate regarding the necessary resources to be deployed to achieve a 100% global renewable energy system. The debate has focused basically on the amount of energy that could be produced by means of renewable sources [3] and whether renewable energy (mainly wind and solar) can fulfill, by itself, the present and future world energy demands given the inherent variability of renewable energy sources [4,5]. The global renewable potential estimated by different studies ranges between a few Terawatts (TW) [6,7] to the more than 250 TW [8], depending on the methodology used for the calculation.

A second crucial question in this debate is about the requirements in terms of available materials and fossil fuels [9–12]. Previous literature concluded that, in general, except from some critical elements the availability of raw materials required by the RT implementation would not be a limiting constraint. However, it has been found that the full implementation of any RT would require significant increase of raw material production [13], which could be a challenge for the mining industry if other economic or industrial sectors demanded additional material production.

Altogether, the transition to a renewable energy production mix is not a matter of a simple substitution, but the result of huge investments of capital, materials and energy. Following this vein, a subject that still urges to be studied in detail is how much energy would be available for fully implementing the RT in a period during which all or most of fossil fuels will be phased out.

---

* Corresponding author.
E-mail address: jsole@icm.csic.es (J. Solé).

https://doi.org/10.1016/j.renene.2017.09.035

Such study has to take into account the rate of decline of the net energy available from current fossil fuels. To do so, two factors need to be further investigated and understood. The first one concerns the amount of net energy that the industrialized society would be able to extract from fossil fuels if only the geological constraints are taken into account. That is, how much fossil fuel net energy we will have at our reach? As it is going to be illustrated below, the non-renewable nature of fossil fuels (at the time scale of a few decades) results on a continuous reduction of the amount of net energy for discretionary uses. The second factor to be addressed, in connection with the reduction of the geophysically available fossil fuel net energy, is the pace of development of renewable resources that is required to balance such decrease of fossil fuel energy production.

In this study, we will not consider all the fossil primary energy sources (including gas or coal), but we will focus only on oil liquids because: i) oil (and particularly crude oil) is a key fuel for global transportation (as it accounts about the 94% of the total energy used for transport [14,15]: and, in turn, transport is a key factor in our globalized economy, thus the behavior of oil liquids production is crucial in economic terms for his role on connecting the flows of goods and services worldwide; and ii) this is the resource whose availability has been studied the most, and whose future production evolution, despite the well-known debate [16,17], has reached the largest consensus among the research community. At present the debate is no longer centered on the fact that curves with a maximum and posterior depletion should be used to represent/forecast the oil liquids production behavior, but on the assumptions on Ultimately Recoverable Resources (URR, thus the amount of resources estimation that can be potentially recoverable, on a given date, plus those quantities already produced therefrom) quantification, on the specific strategies to fit and forecast the production (Sorell et al., 2010 [18–20], and on the dependence of peak oil on prices [21].

The environmental burden, in terms of greenhouse (GHG) emissions associated to the geological depletion of conventional oil, has been revised by Berg and Boland (2013) using recent updates of remaining reserves estimations. The results indicate that, even if the concentration levels of GHG would be lower than previous forecasts by the IPCC (SRES2000), the concentration levels still would surpass the critical threshold of 450 ppm when those reserves are used. The introduction of other fossil fuels for a potential transition to oil substitutes, implies an increase of the environmental concerns, as non-conventional oils and synthetic coal-to-liquids fuels could raise upstream greenhouse (GHG) emissions significantly [18] [1]). Coal is environmentally more GHG polluting and its intensive development in the future, as a substitute of oil, would also have deep environmental implications [22–24]. However, a careful analysis of its availability and climate/ecological impacts is required; in addition, coal production is submitted to depletion as well and forecasts indicate that reserves will run out fast [25–27]. Natural Gas has also been suggested to be a valid resource to support future energy needs [28]. On the other hand, natural gas presents similar environmental problems as oil liquids, mainly related to GHG emissions [29], and its depletion is not either in a distant future [30]. identifies five local pollutants (PM2.5, NOx, SO_2, VOCs and NH_3) and one global emission (CO_2) generated by fossil fuel and traditional bioenergy uses which have health effects (arising from outdoor exposure and indoor exposure) and effects on agriculture. The costs derived from health effects are not supported by the producer but for the public sector, and the effects on agriculture cannot be detected by the producers, but they cause a lower global crop productivity that can be quantified. In both cases the costs are externalized out the production process. The total external costs estimated by IRENA for the base year 2010 amounts between 4.8% and 16.8% of global GDP (or USD 3 trillion-USD 10.5 trillion). The wide range is a result of significant uncertainties for costs associated with air pollution, as well as the assumption about carbon prices. The same report concludes that a doubling of the present renewable share would reduce externalities by USD 1.2–4.2 trillion per year in comparison to current policies. However, markets are unable to translate these costs into correct pricing signals and, therefore, a transition away from oil would require an active support form governments.

Due to such sustainability issues, the assumption here analyzed is to assume that, if there is a decline in the net energy coming from oil, and as a consequence, the future global transport and many other economic sectors appear to be in compromise [31], electricity coming from Renewable Energy Sources (RES) should keep the global net energy supply. The approach followed in this paper is first to estimate the time evolution of the net energy provided by the oil liquids, combining the production forecasts by the International Energy Agency (IEA) with the projections about Energy Return On energy Invested (EROI) of oil liquids. This choice is complemented with two models of Hubbert curves with different estimations of Ultimately Recoverable Resource (URR) [32] and [33]. Three models for the tendency of the EROI decline during the next decades have been used (e.g. Refs. [34,35]. Next, assuming that RES will be used and intensively deployed between 2016 and 2040 in order to fill the energy gap between predicted demand and the decreasing oil liquid net energy production, we evaluate the growth rates in the RES implementation in two different scenarios of global energy supply: a plateau of constant net energy production and a 3% annual growth in the total net energy supply till 2040.

One of the missing points in the current discussions about the necessity of the RES deployment is the rate at which they need to be developed and at what time they must be operational. The objective is to give some guidance to policy makers to plan more accurately the rate of development of the RES.

The paper is structured as follows. In section 2, methods, we introduce the concept of EROI, and we carefully review the IEA projections in terms of available energy, which are the primary data in this study. The projections obtained for the scenarios proposed are discussed in section 3, which is devoted to the presentation of results and to analyze the energy requirements for RT and rates of RES deployment. In section 4, we discuss the main results, and in section 5 we show the conclusions and the policy implications derived from this work.

2. Methods

2.1. Energy Return On energy invested

The EROI is a concept introduced by Charles Hall [36] based on the initial ideas used by Odum [37] to account for the use of energy in ecosystems. Therefore, EROI accounts for what might be called useful or net energy. The EROI is given by the ratio between the energy obtained from a particular energy production technology during its life span and the total energy invested during the whole life cycle of the technology; it can be expressed as:

$$\varepsilon = E_p / E_i, \tag{1}$$

where ε is the EROI, E_p the energy produced and E_i the energy invested to obtain E_p. We define the net energy gain of the system (E_n):

---

[1] We are not formally considering the increasing environmental burden associated with depletion, as it was examined by Refs. [18] and [20].

$$E_n = E_p - E_i. \tag{2}$$

If we express the net energy (E_n) as a function of ε we obtain:

$$\varepsilon = E_p / (E_p - E_n), \tag{3}$$

$$E_n = E_p(1 - 1/\varepsilon). \tag{4}$$

So, for a given constant amount of energy produced, the net energy tends to zero as the EROI reduces to one. Unless otherwise stated, eqs (1)–(4) must be calculated by accounting energy balances over a period of time not shorter than the full life-cycle of the system. Also note that the energy investment has to include all energy costs for manufacturing the materials prior to the deployment of the system, the energy costs of the deployment, the energy costs associated with the system's operation and maintenance, and eventually the costs associated to the decommissioning of the system. This conventional view of the EROI [38,39] is hence static and is adequate to deal with systems (and even societies relying on those systems), which are stationary. However, this view can pose a serious problem when the EROI of a given energy source is not constant [34]. For instance [40], and [23] found that the EROI for oil production in US is related to the level of production and the level of effort (drilling effort) in time. Thus, EROI does not decline steadily in the short term, but both studies find an overall negative trend over decades. In this work we take, for shake of simplicity, a long-term view of the EROI decline and we will suppose, as a simplification, such steady decline already used in Ref. [34].

Due to the non-linear relationship between net energy and EROI, a falling EROI could pass unnoticed until its value gets close to 1, where further reductions would have a significant impacts on the available net energy [35,41,42].

2.2. IEA projection in terms of gross energy

The starting data to estimate the evolution in terms of gross energy come from the Annual World Energy Outlook (WEO) reports issued by the International Energy Agency (IEA) which estimate the evolution of the global production of different liquid hydrocarbons. The data for 2013 and the predicted oil production for 2013–2040 come from Table 3.6 of [43]. These values have been combined with the data from Ref. [44] for the years prior to 2013; in both cases the figures correspond to IEA reference scenario (New Policies). This scenario is taken as the reference of the future oil primary production (Fig. 1a and b).

As the categories of produced volumes of all liquid hydrocarbons do not completely correspond between [44] and [43]; some homogenization has been required. In Ref. [44] there was a category called "Processing Gains" (PG), which is absent in Ref. [43] This corresponds to increases in volume of liquid hydrocarbons after being processed in refineries. The refined fuels may have more energy than the input hydrocarbons because of the upgrading taking place in the refinery, which combines the oil with an additional input of natural gas. Notice however that, according to the Second Law of Thermodynamics, the sum of energies of oil and the employed gas is always greater than the energy of the refined products. We have thus decided to completely disregard this category to avoid double accounting if oil and gas are considered separately, because in fact it does not represent a real increase in the energy of the input liquid hydrocarbons. In addition [43], contains a category, "Enhanced Oil Recovery" (EOR), which was not present in Ref. [44]. We have considered the criterion, maybe too restrictive, that EOR is being employed exclusively in fields that are already in production, and so we accumulate this entry with that of "Fields already in production". This simplification is debatable, not only because some fields experience EOR since the beginning of their production, but also because some fields starting to produce at present would probably be submitted to EOR within the 25-year time span of the IEA forecast.

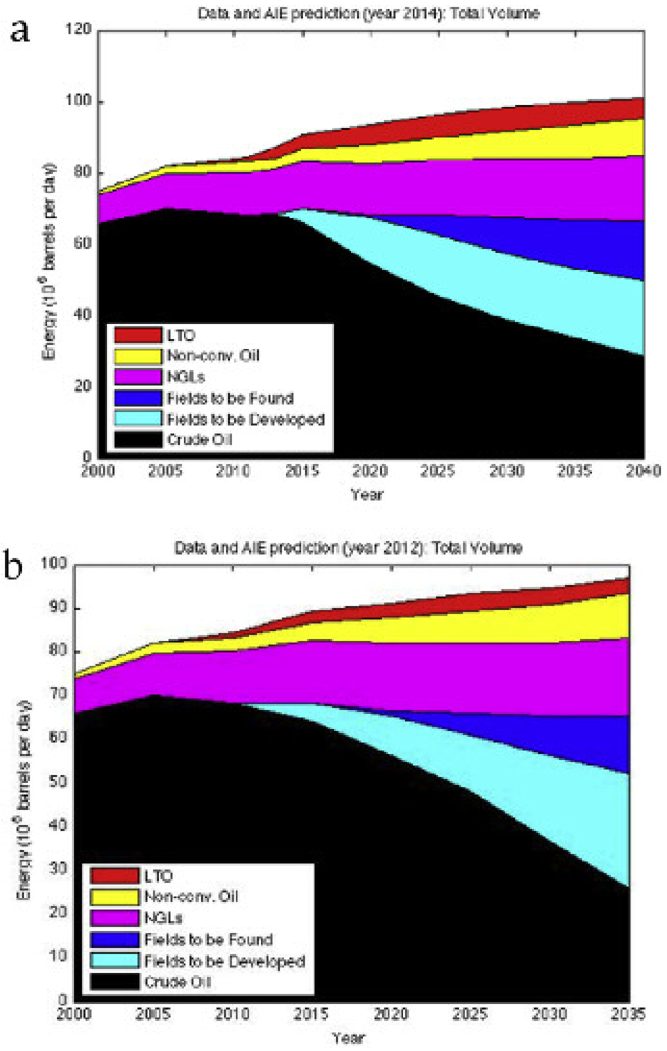

Fig. 1. a) Evolution of the produced volume of all oil liquids, according to the IEA in the "New Policies" scenario according to [43] (data from 2000 to 2011 taken from Ref. [44]. Black, conventional crude oil production from existing fields (2013); cyan, conventional crude oil production coming from fields to be developed; dark blue: conventional crude oil production coming from fields yet to be found; magenta, production of natural gas liquids; yellow: production of non-conventional oil other than Light Tight Oil (LTO); red: LTO. The units in y-axis are millions of barrels per day (Mb/d). b) Evolution of the produced volume of all oil liquids, according to the IEA in the "New Policies" scenario, according to [44]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 1a and b shows clearly that the IEA accounting records a peak of conventional crude oil production (represented by the sum of areas shadowed in black, cyan and blue) some time around 2005. Moreover, the EIA data anticipates a second peak by 2015 if the fields yet to be developed ramp up their production (which seems unlikely in the scenario of relatively low oil prices that started in July 2014 and are still underway during the third quarter of 2015), and a slight decline since 2015 onwards; conventional crude oil production would go from 70 Mb/d in 2005 to 65 Mb/d in 2040. The main drive of this decay is the decline of the conventional crude oil production from already existing fields, which is about 3% per annum during the whole period 2015–2040.

With the inclusion of other sources of liquid hydrocarbons, the IEA estimates that, by 2040, the global production of liquid hydrocarbons would be, in volume, 100.7 Mb/d according to its reference scenario. It is worth noticing that the 100 Mb/d mark was also given for the end of the projected period of the [44] central scenario (see Fig. 1b); although in the case of [44] the end of the projected period was 2035. The estimated production for 2035 in Ref. [43] is very close, 99.8 Mb/d. This coincidence in the expected value of the total volumetric production in both WEOs, at about 100 Mb/d by 2035, is even more striking taking into account the different shapes of the curves derived from Refs. [43] and [44] (see Fig. 1a–b).

In Table 1 we summarize the differences between both scenarios. Table 1 shows that the figures published in the IEA scenarios do not correspond to free forecasts but to forecasts with predefined production targets. For instance, the large difference during the first years of the forecast in the category “Fields to be Developed” (FTD) in Ref. [43] (up to 4.3 Mb/d) is later compensated by a much slower increase by 2035, year at which [44] scenario outpaces that category of [43] by 7 Mb/d. This very large increase in the early years of [43] with respect to those of [44] cannot be explained by the two-year difference in the onset of the category (FTD in Ref. [44] starts in 2013 while in Ref. [43] starts in 2015). This large deviation at the beginning of the forecast period cannot be explained either by the assignment of EOR to the “Existing fields” category in Ref. [43]; because other attribution of EOR should increase “FTD” in Ref. [43] even more with respect to 2012. Besides, the positive deviation in “Existing Fields” and the negative one in “FTD” by 2035 cannot be justified by a possible excessive attribution of EOR to “Existing fields” (the deviations are +8 Mb/d in Existing fields and −7 Mb/d in Fields to be developed, while maximum EOR is 5.8 Mb/d). It is also worth noticing that [43] has a considerable stronger reliance on the evolution of LTO fields but there is not PG category in 2012. Even if we disregard the variations on the other categories, (possible “approximation errors”), the observed differences in “Existing Fields”, “FTD”, “LTO” and “PG” are quite significant, but strikingly the difference between [43] and [44] totals are very similar, as shown in the last column of Table 1.

It is hard to believe that during the two-year period going from 2012 to 2014 the production conditions have really changed so much but, surprisingly, lead to the same round figure of 100 Mb/d total produced volume in 2035. It is thus evident that a production goal has been fixed externally and that the categories are worked according to some loose constraints to attain the production goal. This implies that the prediction values by the IEA should be taken with a bit of caution, as they may be too optimistic about the future of the production of the different categories of liquid hydrocarbons. Indeed, these data do not introduce constraints based on geology or thermodynamics, but consider the energy necessary for a forecasted level of economic activity.

Table 1
Differences in expected produced volumes of liquid hydrocarbons according to category between [43] and [44] (WEO 2014 − WEO 2012); all figures expressed in Mb/d. The labels are as follow: “Existing”: Conventional crude oil from already existing fields; “TBD”: Conventional crude oil from fields to be developed; “TBF”: Conventional crude oil from fields yet to be found; “NGL”: Natural Gas Liquids; “LTO”: Light Tight Oil; “Other”: Other non-conventional; “Total”: The sum of all previous columns; “Total-PG”: As the “Total” column, but subtracting the category “Processing Gains” from Ref. [44].

	Existing	TBD	TBF	NGL	LTO	Other	Total	Total (-PG)
2015	2.1	−0.3	0.1	−1.3	1.1	−0.4	1.3	−1.1
2020	−1.9	4.2	−0.7	−1.0	2.4	−0.6	2.4	−0.5
2025	−2.6	4.3	0.7	−0.8	2.1	−0.7	3.0	0.5
2030	2.0	−1.0	1.4	−0.4	2.9	−1.1	3.8	0.8
2035	8.0	−7.0	0.7	−0.7	2.7	−0.9	2.8	−0.2

The evolution in the production of liquid hydrocarbons shown in Fig. 1a and b refers to the volume (millions of barrels per day) of the oil production. To estimate the resulting gross energy, we need to translate the produced volumes into units of energy (barrels of oil equivalent, boe), because not all of the liquid fractions have the same amount of energy per unit volume. By doing so, we will obtain an estimate of the gross energy of the produced liquid hydrocarbons. All the conversion factors we will estimate for oil liquids to gross energy here are supposed constant along time, which follow our criteria of giving an optimistic calculation for the IEA forecast.

To estimate the energy content of Natural Gas Liquids (NGL) we assume that the fractions of ethane, propane and butane in the world NGL production are the same that the one observed in the US NGL production, i.e. 41% ethane, 30% propane, 13% natural gasoline, 9% isobutene and 7% butane (https://www.energyandincomeadvisor.com/ngl-price-update-the-lighter-end-of-the-barrel/).

The energy contents of these fractions are approximately the following (https://www.neb-one.gc.ca/nrg/tl/cnvrsntbl/cnvrsntbl-eng.html): 18.36 GJ/m^3 (ethane), 25.53 GJ/m^3 (propane), 28.62 GJ/m^3 (butane), The enthalpy of combustion of propane gas include some products losses, for example where the hot gases including water vapor exit a chimney (known as lower heating value) is −2043.455 kJ/mol, which is equivalent to 46.36 MJ/kg. Low heating values of ethane, butane, isobutene and natural gasoline are 47.8, 45.75, 45.61, and 41.2 MJ/kg, respectively.

The density of liquid propane at 25 °C is 493 kg/m^3. Propane expands at 1.5% per −12.22 °C. Thus, liquid propane has a density of approximately 504 kg/m^3 at 15.6 °C and 494 kg/m3 at 25 °C [45]. We assume the following densities for ethane, propane, butane, isobutane and natural gasoline (kg/m^3): 570, 494, 599, 599, 711.

Strictly speaking, ethane should not be considered as an energy resource since it is almost completely used to produce plastics, anti-freeze liquids and detergents (http://www.eia.gov/todayinenergy/detail.cfm?id=5930). However, the IEA statistics regularly includes this fraction of the NGLs in its concept “all liquids” and so we do in this work. Therefore, the energy projections discussed in this work can be considered optimistic estimations.

Light Tight Oil (LTO) denotes conventional oil containing light hydrocarbons, which has been trapped by a non-permeable, non-porous rock such as shale [46] and its energetic content should be not much lower than conventional crude oil.

[47] assumes the same energy content for synthetic oil coming from oil sands and for crude oil. We will assume the same energy content also for other non-conventional oils.

High heating value (HHV) per unit of mass is relatively constant for different type of oils (around $h_m = 45.54$ J/kg), due to the fact that most HCs fractions in oil are close to the molecular formula $(CH_2)_n$, where CH_2 is the basic building module of linear HCs. Thus, to calculate the HHV per volume unit h_v (J/m^3) of unconventional oils we will use the following formula:

$$h_v = 45.54\,\rho \tag{5}$$

where ρ is the fuel density after upgrading, which is related to the API degrees, a measure of how heavy or light a petroleum liquid is, compared to water [48]:

$$\rho = \rho_w \left[\frac{141.5}{API + 131.5}\right], \tag{6}$$

where ρ_w is water density (1000 kg/m^3).

According to [49]; the upgrading of bitumen (with 8° API) to *syncrude* (with 31–33° API for the “*syncrude sweet blend*”) is made in two steps. A first partial upgrade produces a pipeline quality

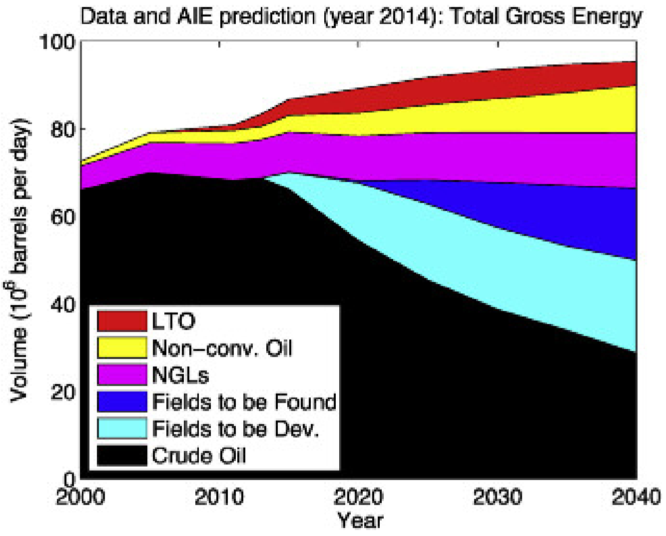

Fig. 2. Evolution of gross energy content of all liquids according to the volume data given by IEA [43] and the assumptions made in the text.

crude of 20–25° API. The second (full) upgrade produces a final product, which is similar to conventional oil. An alternative to the first step is to dilute the bitumen with natural gas liquids to produce "*dilbit*" with 21.5° API approximately. By assuming a final product of 32° API in all the cases, the oil density of upgraded bitumen is 865 kg/m3.

The upgrading of kerogen is different to the one of bitumen, but the final product is an oil of 30° API approximately [50], or 876 kg/m3.

We assume that the mean density of upgraded unconventional oils is the average of the last two densities, i.e. 870.5 kg/m3. According to US Oil (2014) the apparent density of an standard oil barrel of 159 L and 1 BOE of energy content (HHV) is 845.5 kg/m3. Thus, the energy content of one barrel of unconventional oil is practically equal to that of a standard oil barrel.

With these assumptions, the aggregate gross energy contribution of all liquids and their components as they evolve along time can be obtained, and they are represented in Fig. 2. We can observe how total gross energy of oil liquids is growing to a total amount of 95.3 Mboe/day in 2040 with a decay of Crude Oil (with 29 Mboe/day in 2040) compensated by the categories of "Fields to be Found" (FTF) and FTD.

2.3. Oil production

We made an alternative estimation of the all liquids evolution with the help of a Hubbert fit of historical gross energy production that uses [51] estimation of the Ultimately Recoverable Resource (URR).

The historical data of production has been taken from The Shift Project data portal,[2] which take them from Ref. [52] and the US EIA historical statistics.

For future world consumption, the historical oil data has been adjusted using a combination of two "Hubbert" functions of the form:

$$P = \frac{fug_1 e^{-g_1(t-t_1)}}{\left[1+e^{-g_1(t-t_1)}\right]^2} + \frac{(1-f)ug_2 e^{-g_2(t-t_2)}}{\left[1+e^{-g_2(t-t_2)}\right]^2} \qquad (7)$$

Where P is the annual production of oil liquids, u is its ultimately recoverable resource (URR), f the fraction of u that belongs to the first logistic function, $g_{1,2}$ is the growth rate parameter of the two logistic functions, and $t_{1,2}$ the year of peak production of the two logistics.

A good estimate of u (Ultimately Recoverable Resource) is important in reducing the number of free parameters in the fit to only g and t_p. The total petroleum resource estimated to be recoverable from a given area (which differs from the total "oil in place", since not all may be recoverable) is the *ultimately recoverable resource* (URR) for that area. At any point in time, the URR is equivalent to the sum of cumulative production, remaining reserves, and the estimated recoverable resources from undiscovered deposits - normally called "yet-to-find" (YTF) [53].

In our fit, URR is just the area of the curve, and it strongly constrains the curve shape so decreasing the uncertainty of g and t_p. After obtaining these two parameters the resulting function is used to forecast future production rates.

The URR for oil liquids has been estimated by Refs. [51,54] to be 3×10^{12} boe, about 400–420 Gtoe. Taking the largest value, 17580 EJ are obtained for the parameter u. A nonlinear best Mean square root fit with $R^2 = 0.999$ is obtained for the following parameters: $f = 0.07$, $g_1 = 0.049$, $t_1 = 2021$, $g_2 = 0.155$, $t_2 = 1977$. To compensate possible pessimistic bias an alternative URR of 4×10^{12} boe has been also used in the fitting. This figure is close to the upper value used by Ref. [32] for the URR of conventional oil, which has been considered to be larger than the actual URR with 95% probability [55].

Fig. 3a shows the two fits obtained until 2050 and Fig. 3b compares the total energy projection obtained with IEA data (gray continuous line) with the one obtained from the pessimistic Hubbert fit (black dashed line) and the optimistic Hubbert fit (gray dashed line). The projections of IEA and pessimistic fit have a similar evolution within an error bar of 5–10 EJ/yr from 2010 to 2021. After 2021 the IEA projection continues its growth and markedly separates from our pessimistic fit, which declines. This projection would be consistent with a URR larger than 3 Tboe, for instance an URR = 4 Tboe would be amply capable to feed a sustained increase of oil production until 2040. However, when the FTF are removed from the IEA fractions, the IEA projection so modified (dotted line) becomes closer to the pessimistic fit with an error of 5–10 EJ/yr until 2035. After that year, the two curves separate due to their different decay rate, which is linear for IEA and exponential for the fit. The black continuous line in the figure corresponds to the historical data from TSP portal used for the Hubbert fits.

3. Results

3.1. Net energy in a global economy based on fossil fuels

From Fig. 2 of gross energy estimation, we can estimate the net energy using the definition of EROI. As a first approximation, we have assumed that EROI is different for each type of hydrocarbon but constant in time, so we have obtained the estimates of net energy production for the 5 types shown in Fig. 2. We have assumed EROI = 20 for existing fields of conventional crude oil [42]. For fields to be developed, we have assumed that an EROI of 10, half the value for existing fields, which is a compromise between the EROI from non-conventional oil and the EROI for existing fields [56]. We have estimated the EROI for natural gas liquids taking into account an EROI of 10 reported for natural gas and the energy

---

[2] TSP data portal is an information platform that provides immediate and free access to a wide range of global energy and climate statistics, http://www.tsp-data-portal.org/.

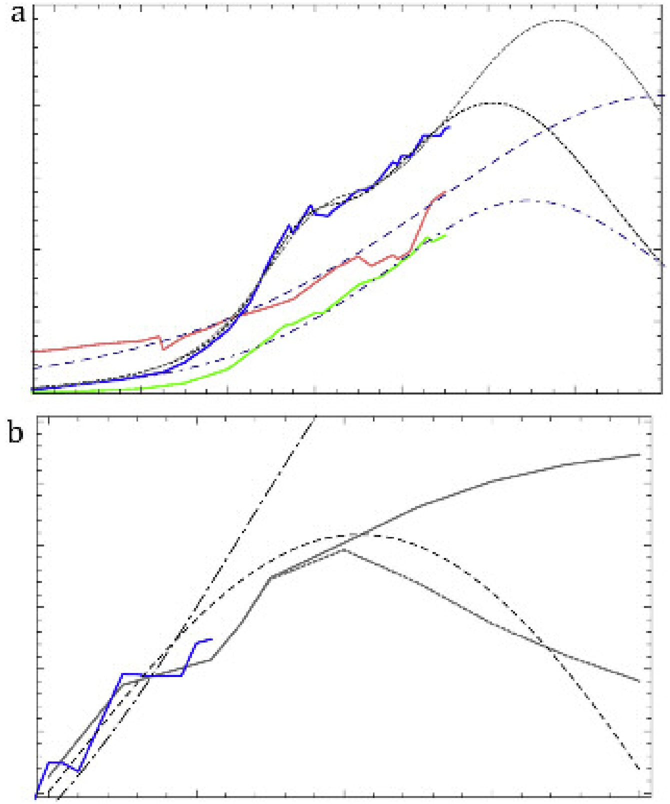

Fig. 3. a) Fit of historical data of oil, coal and gas production to a Hubbert curve with a URR parameter obtained by Ref. [51] with dashed line, and by Ref. [32] with pointed line (see text). b) Total energy along time according to: SPD (black continuous line), IEA (gray continuous line), IEA without the fraction "fields to be found" (dotted line), our Hubbert fit (dashed line) and the estimated following Kaufmann and Shiers (dashed-doted line).

needed to separate the NGL fractions; the result is EROI = 7.7. Finally, for non-conventional oil we assume that 80% of it is "mined" and 20% "in situ" exploitation, with EROIs of 2.9 and 5 respectively [57]. The combined EROI of non-conventional is estimated by averaging the gross energy inputs for each unit of produced energy, what implies that the combined EROI is estimated as the inverse of the average of the inverses of both types of EROI, namely:

$$\varepsilon_{un} = [0.8(2.9)^{-1}+0.2(5)^{-1}]^{-1} \cong 3.2$$

Light Tight Oil is energetically expensive to extract [57], but has no need of upgrading; thus, we assume for it the same EROI, 5, as for tar sands without upgrading [57]. Fields to be found are assumed to be at high depth and/or sea locations and having the same EROI. The EROI used for each liquid is resumed in Table 2.

The net energy for every oil liquid fraction is displayed in aggregate form in Fig. 4. We can see that, since 2015, the aggregate net energy available from oil liquids is almost constant, reaching a value slightly higher than 80 million barrels of oil equivalent (in net energy) per day by 2040.

A more precise calculation on net energy requires that EROI of each non-renewable resource will decrease during the next decades because depletion tends to increase the energy invested in extraction (E_i in eq. (1)) [34]. proposed two functional dependencies for EROI decrease with time, linear (hereafter L model) and exponential (hereafter E model), for pessimistic and optimistic cases, respectively:

$$\varepsilon(t) = \varepsilon_{2013} - \delta(t - 2013) \tag{8}$$

$$\varepsilon(t) = \varepsilon_{2013} - exp\left(\frac{t - 2013}{\tau}\right) \tag{9}$$

The parameter ε_{2013} is the initial value of EROI at the reference year 2013. In what follows we will assume $\delta = 0.25$ year^{-1} (in the L model) and $\tau = 43$ year (in the E model). Those values correspond to the scenario of intermediate exponential variation and gradual linear variation, respectively, in the work of [34]. It should be noticed that the minimum value that $\varepsilon(t)$ is allowed to take is 1. For EROI values below 1 the hydrocarbon will no longer be a source but a drain of energy and hence we assume that its production would be discontinued.

Fig. 5a shows the net energy obtained when L model, eq. (8), is used. Net energy is the same than in Fig. 4 until 2015 and after that year it decreases as shown in Fig. 5a. Fig. 5b represents the net energy obtained when E model, eq. (9), is used.

As shown in Fig. 5a–b, both models predict a peak of net energy approximately at 2015, with an uncertainty of a few years because the time resolution of data is 5 years. The decline is quite sharp in the case of the linear function. In addition, for this model (Fig. 5a), all the sources, except conventional crude oil from existing fields and fields to be developed, are completely depleted (in terms of net energy) by 2030. In the exponential decay model (Fig. 5b) the decline estimated after 2015 is smoother and takes the net energy from 80 to 70 Mboe/d by the end of the period.

A different model for the future evolution of oil EROI was proposed by Ref. [58] and consists in a quadratic decline of EROI as a function of the fraction of Ultimately Recoverable Resource (URR) that has not been extracted ($R_f(t)$). The remaining fraction of total oil can be calculated for each year from the area of the corresponding Hubbert curve displayed in Fig. 2-a. Then the EROI for the different oil components is modeled in the following way:

Table 2
EROI of the different oil liquids considered to calculate the results in Fig. 2.

	Crude Oil	TBD	TBF	NGL	NCO	LTO
EROI	20	10	5	7.7	3.2	5

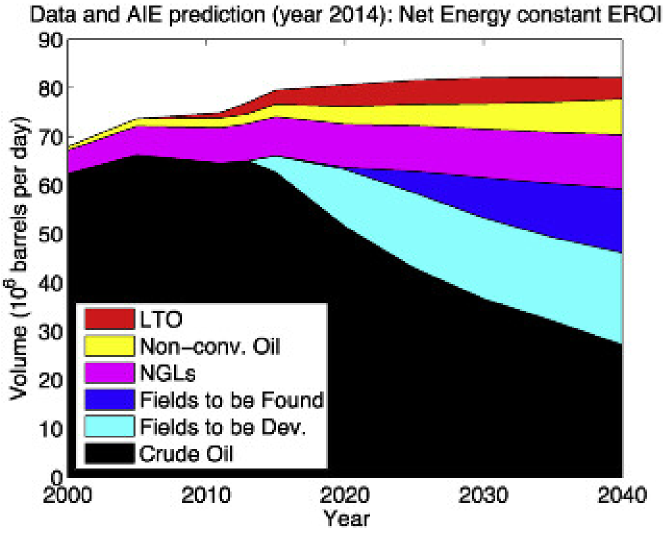

Fig. 4. Net energy (constant EROI) of Oil liquids [43] and its estimate evolution till 2040.

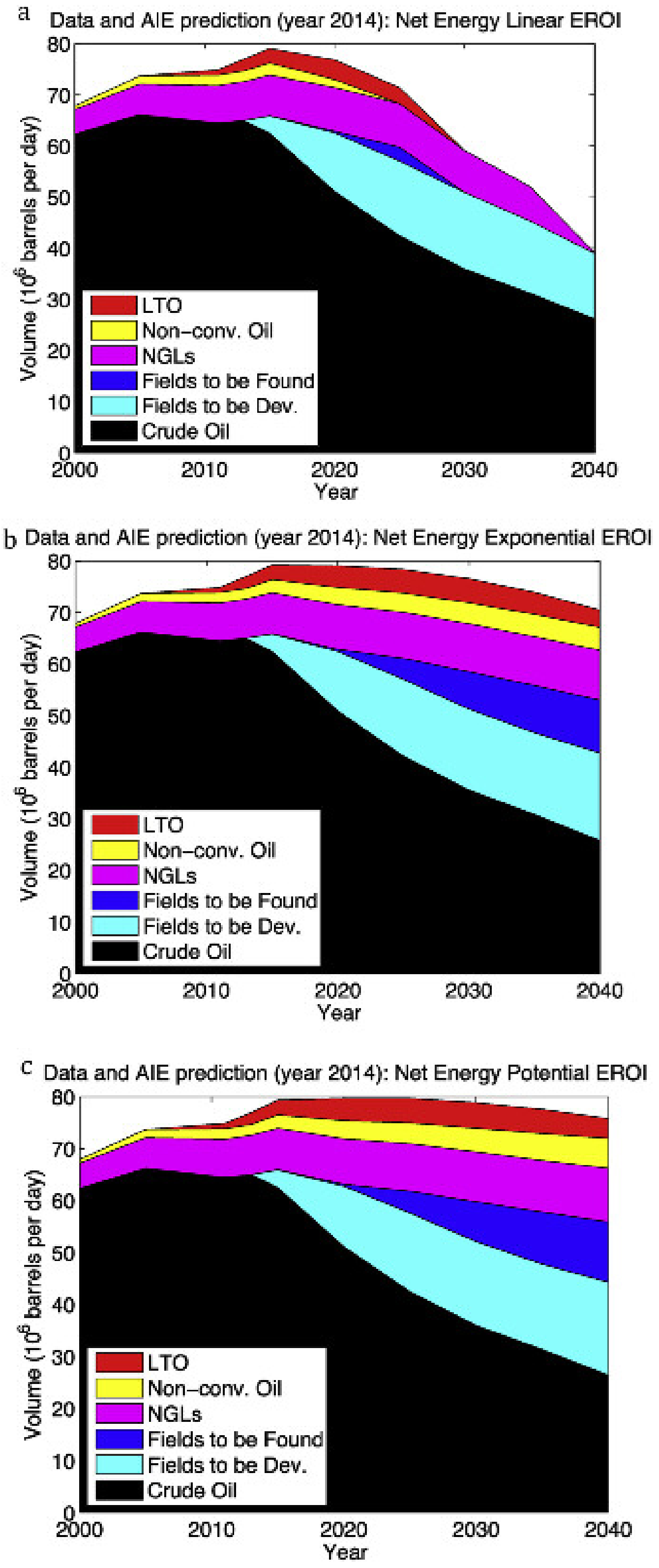

Fig. 5. a) Estimation of the net energy of the oil liquids reported by Ref. [43] when a linear model is used for modeling the EROI decrease. b) same as a) when an exponential model is used for modeling the EROI decrease. c) same as a) obtained with an EROI potentially dependent on the remaining fraction of oil.

$$\varepsilon_j(t) = k_j R_j(t)^p \ \text{t} > 2013 \tag{10}$$

where $k_j = [\varepsilon_j(2013)\text{-}\ \varepsilon_{\infty j}]/R_j(2013)^p$, for component j of oil and t is the year. This expression predicts that the oil EROI takes its observed value at 2013 and tends asymptotically to zero in the long term. [33]; see Supplementary Material) obtained $p = 3.3$, a value providing an appropriate fit to the observed decay of EROI between 1900 and 2010, and it is the value used in this work. The estimation for the net energy obtained with this potential model (hereafter P model) is displayed in Fig. 5c. It can be appreciated how the forecast for this model gives a more optimistic approach than the two previous, with a slow decay of all net energy liquids including a small growth of net energy around 2020-25 with a final value around 75 Mb/d.

3.2. *Renewable transition and rates of deployment of RES*

In the previous sections, all the models considered show the net energy decay for liquid hydrocarbons during the next 25 years. In this section we will analyze the pace of development of RES to compensate this net energy decay. Two limiting rates of RES deployment will be studied here, namely the maximum and the minimum rates for a time period going from 2015 to 2040. In the context of this work, we just want to identify any possible constraints that the decline in available net energy from liquid hydrocarbons would impose on the RES deployment. Regarding the maximum rate, we want to know if a full replacement of all energy sources by RES is possible during the period. Regarding the minimum rate of RES deployment, we want to assess the necessary growth rate in RES development, under the different scenarios, to be able to keep pace with the world energy demand once liquid hydrocarbon decline is accounted.

3.2.1. *Energy cost of the new infrastructure required for taking profit of a 100% renewable system*

Implementation of a RT satisfying all the energy needs of humanity would involve using a fraction of the non-renewable energy production to build and maintain the energy production and transmission infrastructure, to extract and process materials (prospecting resources and investment in mining), to restructure the heavy industrial sector (among others, restructuring the automotive industry) and to develop unconventional industrial and agricultural activities. To evaluate the order of magnitude of the total net energy required for the RT we estimated the energy required for some of the main changes in infrastructures necessary for such RT. We have considered the 2015 economic cost (in dollars), multiplied by the energetic intensity (0.57 Mboe/$15) of World industry.

We have considered energetic costs of (Table 3 shows the parameters used):

i) the interconnection between distant areas (using the distances estimated in Ref. [46] and fabrication of electrical vehicles. The costs from electrification of railroad transport have not been calculated since, to be conservative, we have assumed that the transport model would remain being automotive-based. In fact, basing transport mainly on electric trains would save probably an important fraction of the cost estimated. Our estimations give for this sector: 118.6 Gboe (10^9 barrels of oil equivalent),
ii) Domestic heating and cooling: we consider a mean domestic surface of heating and cooling of 20 square meters per person in the world and we study two main areas: tropical and temperate zones. We take the 45% of World population living in tropical areas and 55% living in temperate areas for the period 2015−2040. The total cost estimated for this sector is: 1.17 Gboe.
iii) Mining and processing of copper and iron. We will need to produce a total of 5398 Mt (10^6 metric tons) of iron and steel,

Table 3
Parameters used in the estimation of energy cost of RE infrastructure.

Parameter	Units	Value	Reference
Length of HVDC connections	km	33 300	[10]
Total power transmitted	TW (10^{12} W)	10	1-2 TW from local and regional photovoltaics [59]
Cost of HVDC lines	\$ $MW^{-1}km^{-1}$	500	[60,61]
Industry energy intensity	Koe/\$15p[a]	0.081	(https://www.wec-indicators.enerdata.eu/industry-energy-intensity-world-level-trends.html
Number of motorcycles, light andheavy vehicles	millions	270 /584 /240	[10]
Price of a electric motorcycle, car and truck	euros	5000 /20000 /90000	Authors' estimations from 2015 marketprices in Spain
Area of a 4-people home	m^2	80	Based on: http://reneweconomy.com.au/2013/how-big-is-a-house-average-house-size-by-country-78685
Power needed for home heating at temperate latitudes and tropics	W/m^2	100 /0	http://www.clickrenovables.com/blog/como-calcular-la-potencia-las-necesidades-de-combustible-y-el-ahorro-que-obtienes-con-una-instalacion-de-biomasa-caso-practico-y-comparativa/
Population in temperate latitudes and tropics	millions	4263 /3487	Mean estimated for 2015–2040 based on [62]; "medium scenario"
Price of an electric combiboiler 8 kW	euros	1283	Based on the price in Spain of the Gabarron CMX-15 combiboiler
Price of a heat pump for 12 kW of heating	euros	1559	Based on the price in Spain of the Meeting MD30D
Mass of steel in RE devicesand vehicles	Million tonnes	5398	Based on [10]
Energy for industry steel production	GJ/t	22.7	Based on: [63,64]
Energy for iron mining	GJ/t	1 GJ/t	[13]
Mass of copper in RE devices and vehicles	Million tonnes	330	[10]
Energy for mining and processing of Cu	GJ/t	33	[13]

[a] Koe: kg of oil equivalent; \$15p: dollars at constant exchange rate, price and purchasing power parities of the year 2015.

with an energetic cost of 22.7 GJ/t for mining and producing steel and 23.7 GJ/t for iron mining and production, which considering ovens (regular and of electric arch) used by steel industry gives a total of 238 EJ (10^{18} J) for iron and 10.9 EJ for copper, which is a total amount of 40.7 Gboe.

These costs together give a total cost of 160.5 Gboe for such necessary changes, which should be taken into account during the evaluation of the energetic costs of RES development (installation and maintenance). This amount of required energy, 160.5 Gboe, is quite impressive: if the transition were to take 25 years this would imply an average energy flux of about 17.6 Mboe/day. Just to have a reference, such energy expense compared to the net energy annually provided by liquid hydrocarbons would represent 22% in 2015 and up to 44% -in L model-by 2040; compared to the total amount of primary energy currently consumed in the world this would represent a bit more than 7%. However, this expense should not be accounted the same way as the cost for implementing the new renewable systems, because what it implies is a shift in the uses assigned to energy. Indeed, some of the required changes will imply an increase of energy consumption with respect to the present consumption patterns and somehow an actual cost, but at the same time some new activities will imply a decreased consumption of energy and materials with respect to those activities replaced by them. Thus, evaluating the net cost of the transition in terms of the required infrastructures implies carrying a very detailed study on the many affected sectors, which exceeds by far the frame of the present work.

3.2.2. *Impacts of considering coal, gas and biofuels to compensate oil depletion in transportation*

We analyze in this subsection the transition scenario of using gas and coal to compensate the oil net energy depletion. We only consider the effect that will have the oil depletion in the global transport. In this line, we analyze two main aspects: the effect of oil depletion in transportation and their substitution by oil and gas and the use of biofuels to compensate such depletion.

If coal and gas energy will be used by transport sector to support the RT, filling the decay in oil net energy, then we can consider two cases: 1) energy coming from coal and gas or only from gas and 2) energy coming from renewable electricity. For these estimations we considered the potential model for EROI decay. We consider that the EROI decay for gas will be the same than for oil liquids and that for coal it will be constant.

1) Oil decay compensated by using coal and gas or only gas to produce electricity with which to power the transport. We will assume that the vehicles fleet is already 100% electricity-powered. The efficiencies would be: about 0.42 for the electricity production and transmission [14] and 0.67 for the plug-to-wheel efficiency of a battery vehicle [65]. This gives an efficiency of 0.281 for the process primary energy production to wheel. In contrast, the current efficiency well to wheel of a gasoline vehicle would be $0.92 \times 0.16 = 0.147$. Here, we have considered that refining self-consumption and transport of fuels use 8% of the primary oil [14] and that the tank-to-wheel efficiency of an internal combustion vehicle is about 0.16 [65,66]. If we divide this efficiency by the previous one the result is a 0.52 factor. Thus if we consider the oil depletion substitution by coal and gas then the sum of the two fuels must be greater than 0.52 of the oil decline. If, due to environmental reasons, coal is avoided and we only substitute the oil depletion by gas then the gas production must be 0.52 greater than the oil decline (see Fig. 7).
2) Oil decay compensated by using renewable electricity and battery cars. We will assume an efficiency of 0.93 (7% of losses) for the electricity transmission of a future grid connecting renewable stations and consumption points [10]. Using the plug-to-wheel efficiency given above for battery vehicles (0.67) the production-to-wheel efficiency obtained is 0.623. The ratio of the well-to-wheel efficiency of an internal combustion vehicle (0.147) and the previos figure (0.67) is 0.236. Thus, if only renewable electricity and vehicles with batteries are used then the increase of renewables must be at least 0.236 times the oil decline (Fig. 7).

Another option, as has been commented previously, is to use biofuels to compensate the oil liquids decline in transportation

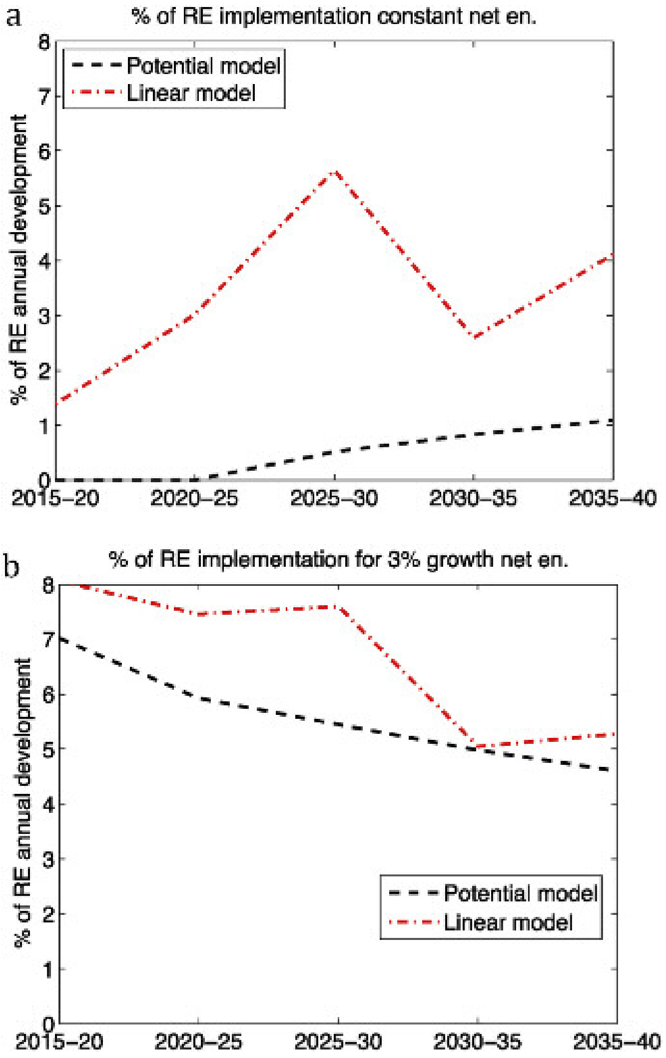

Fig. 6. a) % of RE annual development for constant (as in 2015) future net energy production in two models of EROI decay: L (red line) and P (black line). b) % of RE annual development of 3% grow of total net energy (starting in 2015 net energy estimations) in two models of EROI decay: L (red line) and P (black line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

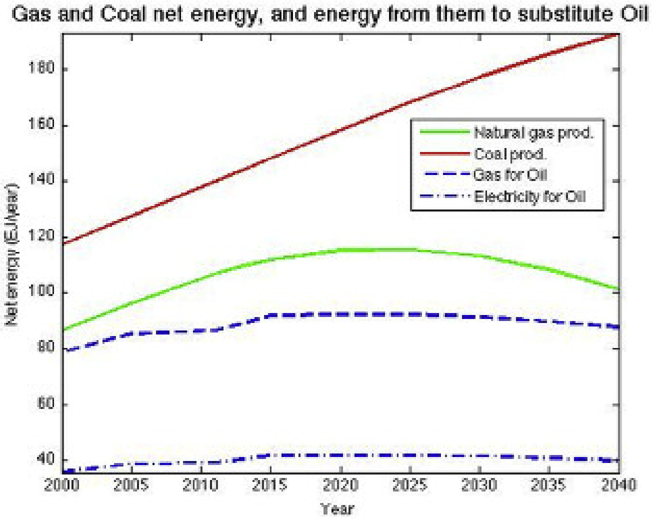

Fig. 7. Evolution of the net energy from coal (red line) and gas (Green line) and the necessary energy to compensate the oil liquids decline with the EROI potential model. In blue (dashed line) it is shown the necessary energy for the transport coming from coal and gas to compensate the oil depletion and the net energy necessary in case such energy comes only from renewable energy and plug-in vehicles (blue dot-dashed line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

[67–69], specially in the marine and air sectors, since batteries have severe limitations in long distance and high power transport. A mean fixed cost of transportation of bio oil by truck is 5.7$10/m3 (by $10 we mean USD of 2010). The energy consumed by the air and marine transport in 2005 was 285 and 330 GWy/y (based on [14]. The [70] projected a demand of energy by the transport between 120 and 160 EJ/y in 2040 [70]. Taking 120 EJ/y as the more probable figure, if a renewable transition is started, this figure is equivalent to 3.8 TWy/y (1 TWy/y = 31.54 EJ/y). The scale factor for energy consumption between 2005 and 2040 would be 1.31. Assuming that the scale factor is appropriate for both air and marine transport, these sectors would demand 373 and 433 GWy/y, respectively, in 2040. We assume that both sectors would use mainly liquid fuels. Assuming that 50% of the total demand of energy by these sectors must be already supplied by bio-fuels in 2040, 403 GWy/y of bio-fuels should be produced and transported that year [71,72]. A typical value of the lower heating value of Liquified Natural Gas (LNG) apt to be transported by truck and ship is 20300 MJ/m3 (Wiki ‘Liquified Natural Gas’). Assuming that a small fraction of LNG will be transported by ship and adding by the inflation 2010–2017, the final cost would be 4.4 × 10^9 USD or, using the energy intensity of world industry (0.081 kboe/$15), about 3 Mboe of energy embodied. This figure is three orders of magnitude lower than the energy cost of renewing the air conditioning worldwide, four orders of magnitude lower than renewing the vehicles fleet and five orders of magnitude than building the new electric infrastructure (see Section 3.2.1). Thus, the deployment of a gas transport grid would be a relatively minor problem in the transition.

3.2.3. *Constraints on the maximum rate of RES deployment*

According to the U.S. Energy Information Administration [73], the global annual total primary energy consumption from 2008 to 2012 was 512, 506, 536, 549 and 552 EJ (1 EJ = 10^{18} J), which correspond to an average power of 16.2, 16.0, 17.0, 17.4 and 17.5 TW. To calculate the energy cost of the renewable transition, we assume a goal of having 11 TW of average power by 2040, which implies that, by that year, we should produce the equivalent to 155 Mboe per day with renewable energy sources. These 11 TW are assumed to be enough to replace 16 TW produced by non-renewable sources, if one implicitly assumes a gain in terms of efficiency when using electricity as the energy carrier or equivalently some conservative policy to save energy [10,74]. We assume an EROI of 20 for renewable sources, constant along time, both for wind and solar concentration power [10]. Hence, to produce 155 Mboe per day we would have to invest the twentieth part of the energy produced in its construction and maintenance. We assume this investment will be mainly provided by crude oil during that period, at a constant pace. We start with a production of renewable energy that is today 13% of all primary energy, and we assume that 100% is reached in 2040. For the sake of simplicity, to assess the maximum rate of deployment, we assume an implementation of RES, which grows linearly with time.

Here, we consider the evolution in net energy from all oil liquids in three scenarios, each one in agreement with each of our three models (L, P and E) (Fig. 5a, b and c); a part of the available oil energy will be directed (energy invested) to the renewable

Table 4
Maximum energy required for RT in each of the three models of EROI decay: linear (L), exponential (E) and potential (P), expressed both as mboe/d and as % of total oil net energy production required according to each model.

	2015	2020	2025	2030	2035	2040
Model L: Amount of energy required (mb/d)	1.23	1.87	2.41	3.22	3.92	5.22
Model L: % of crude oil energy required	1.9	3.6	5.6	8.9	12.5	19.8
Model E: Amount of energy required (mb/d)	1.23	1.81	2.18	2.46	2.73	2.85
Model E: % of crude oil energy required	1.9	3.5	5.1	6.9	8.8	11
Model P: Amount of energy required (mb/d)	1.23	1.8	2.16	2.42	2.64	2.71
Model P: % of crude oil energy required	1.9	3.5	5	6.7	8.4	10.2

Table 5
Constant energy production scenario. Energy replacement time evolution (in mb/d and TWh) and percentage of RES growth for models L and P.

Scenario constant	2015–20	2020–25	2025–30	2030–35	2035–40
Model L: Additional required power (Mb/d)	2.2	5.3	12.3	7.0	13.0
Model L: Additional required power (Twh/year)	1365	3288	7632	4343	8066
Model L: Annualized rate	1.3	2.8	5.6	2.6	4.1
Model P: Additional required power (Mb/d)	0	0	0.8	1.3	1.7
Model P: Additional required power (TWh/year)	0	0	502	816	1082
Model P: Annualized rate	0	0	0.5	0.8	1.0

deployment.

In all cases the implementation of RT will be feasible in terms of available crude oil net energy. According to Table 4, the maximum required percentage of produced crude oil net energy occurs in the L model by 2040, attaining almost 20%; in contrast, with P model just 10% is required by that year. The intermediate scenario (E) requires 2.85 Mboe per day, which is 11% of the total 2040 net energy of crude oil.

3.2.4. *Constraints on the minimum rate of RES deployment*

The second question addressed here deals with the minimal rate of RES deployment required to fulfill the global net energy demand at any moment, especially taking into account that the decline in net energy may impose large annual rates of change. We start with the amount of RES available in 2015, which we consider the same as in the previous subsection: 13.9% of all primary energy, i.e. 31.3 Mboe/d or 19420 TWh (using the equivalence 1 boe = 1.7 MWh). Then, we will calculate the necessary rate of deployment to compensate the fall in net energy from liquid hydrocarbons. To simplify the discussion, only L and P models will be used, which represent optimistic and pessimistic cases. Two different future net energy supply scenarios will be considered. In the first one, we will assume that RES net energy production compensates in the long-term tendency the net energy decay in liquid hydrocarbons: the sum of RES and liquid hydrocarbon net energy is constant. We acknowledge here that this is an oversimplification, as previous studies have shown that there are short-term oscillations in the EROI time evolution [23,40] that conducts always to total net energy decays. However, our objective is to focus in the long-term tendency of EROI and to give some optimistic limits considering the hypothesis of [34]. We will call this scenario of constant sum of net energy of RES and oil liquids the *constant scenario*. In the second one, we will assume that RES deployment not only compensates the long-term net energy decay of liquid hydrocarbons but that it provides an additional 3% yearly increase of net energy production from the level given by liquid hydrocarbons from 2015 to 2040. We will call this the *growth scenario*. This 3% growth can be understood as a 2% of net energy growth necessary for the economic growth plus a 1% due to the expected increase of global population, according to the forecasts of UN (http://esa.un.org/unpd/wpp/Graphs/). Notice that the growth scenario is in fact a quite optimistic one, as the rate of growth is lower than the historical rates of growth in oil production.

For each 5-year period, an annualized rate of RES growth will be calculated:

$$\mu_i = (1+\Delta p_i / r_{i-1})^{1/5} - 1 \tag{12}$$

where Δp_i is the decay + growth (if any) in liquid hydrocarbon energy for the i-th 5-year period and r_i stands for the amount of RES at period i; then, we can estimate RES for the following period once the annualized rated is known in the present period by means of the formula:

$$r_i = r_{i-1}(1+\mu_i)^5 = r_{i-1} + \Delta p_i \tag{13}$$

The results of the constant and growth scenarios are shown in Fig. 6a and b and Tables 5 and 6 The results for model L and P are given, expressing for each 5-year period the requirements of energy rate increase of RES to fulfill that mark. Fig. 6a shows the results for the constant scenario, while Fig. 6b refers to the growth scenario. As model L forecasts a faster decay, it consequently implies a higher RES increase to compensate it. In the case of constant scenario (Fig. 6a, Table 5), model L indicates that by 2040 RES should have

Table 6
Growing energy production scenario. Energy replacement, time evolution (in mb/d and TWh) and percentage of RES growth for models L and P.

Scenario growth	2015–20	2020–25	2025–30	2030–35	2035–40
Model L: Additional required power (Mb/d)	15	20	29.2	26.6	35.7
Model L: Additional required power (Twh/year)	9160	12345	18066	16453	22092
Model L: Annualized rate	8.05	7.46	7.6	5.05	5.27
Model P: Additional required power (Mb/d)	12.6	14.6	17.8	21	24.5
Model P: Additional required power (Twh/year)	7815	9060	11006	12993	15198
Model P: Annualized rate	7.01	6	5.4	5	4.6

been increased by at least 105% from present value, passing from 19420 TWh in year 2015 to a minimum of 39814 TWh in year 2040, while the minimum required raise would be of just 1.4% in the case of model P, only 22460 TWh by 2040. The largest annualized rate of growth is observed in model L for the period 2025–2030, when the annual growth should be of at least 5.6% per year (Fig. 6a and Table 5).

The situation is stringent in the case of the growth scenario (Fig. 6b and Table 6), where the RES deployment must not only compensate the net energy decay in the liquid hydrocarbons but also produce an additional contribution to reach the proposed 3% increase. The minimum annual rates of change are always above 4% annual for all considered periods in both models L and P, and for one period in model L this required minimum (again, 2015–2020) is 8% per each of the five years in the period. Notice, however, that each 5-year period in which the transition to RES is postponed, implies a substantial increase on the required minimum of average annual rate. So, for the full period 2015–2040 the average annual rate in the growth scenario is 5.6% in model L and 3.8% in model P; but if the transition is delayed to 2020 the required mean annual rates of increase (for a period of 20 years) in RES deployment will be of 8.3% (L model) and 6.9% (P model). If the transition is postponed 10 years from the present, the required mean annual rates (for all the 15 years) will be 11.1% (L model) and 9.3% (P model).

4. Discussion

In this article we have used the IEA forecasts of the global production of different liquid hydrocarbons [43] with three projections of Energy Return On energy Investment (EROI or EROEI) to provide estimates of the amount of net energy that will be available from oil for discretionary uses in the next decades. Taking into account the gross energy equivalences, the total gross energy will grow up to 95 Mboe per day till 2040. This quantity makes an adjustment of the WEO forecast by around 5 Mboe per day less for the total volume. When these IEA estimates are compared with two fits of a Hubbert function (following [32] and [33], all projections have a similar evolution within an error bar of 5–10 EJ/yr for the period 2010–2021. After 2021, IEA projects a continuous growth markedly separating from our Hubbert fits, which decline. However, when the "fields to be discovered" are removed from the IEA fractions, the IEA projection evolves close to the Hubbert fit, with an error of 5–10 EJ/yr until 2035. This fact points out that IEA estimations likely rely on the category "fields to be found" to fulfill the necessary growth of production till 2040. This evidence casts a word of warning on the rest of our analysis. That is, our results are more optimistic than if more realistic projections had been considered.

An important point is that estimates of oil liquids evolution in Ref. [43] did not consider how the production of gross energy translates into net energy, that is, in energy available to society for uses different of producing more energy. Our analysis taking into account the EROI shows that the production of net energy stagnates around 80 Mboe/d during the whole period till 2040. Studies on the EROI evolution have shown that EROI may exhibit rapid oscillations and short-term variability due to punctual investments and efficiency improvements [56,75]. However such behavior does not avoid a systematic decay at long term. It is on this context that we have considered three scenarios to assess the potential future evolution of liquid hydrocarbons, considering three smoothed models of EROI: linear, exponential and potential.

Whatever the model used, the maximum of net energy production is around 2015–2020. Only crude oil keeps its production with almost no net contribution by any other source of liquids in the EROI linear model by 2040, giving a total amount of around 39 Mboe/d in that year. The other two models lead to a significant reduction in the production, 75 Mboe/d and 70 Mboe/d in the potential and exponential model respectively, and quite different with respect to the linear one in which all liquids still contribute to the net energy by 2040. We see in this analysis that even in the most optimistic model (potential) there is a reduction with respect to [43] forecast in terms of the total World production of liquid hydrocarbon net energy, placing the projected growth of global total gross energy supply under serious stress.

To overcome this problems the implementation of a RT requires other energy investments that should be considered as a part of the development of renewables: transport electrification, industry adaptation from fossil to electric technologies, changes and extension of the electric grid from the geographical renewable production center to the end-users and consumers, energy storage, small-scale energy producers, and industrial large-scale RES production. Here we have made a rough evaluation of some of such issues (mining, heating and cooling, electric grid installation and transport electrification), which amounts to around 160.5Gboe, and that has to be considered as a first estimation for future evaluations and discussions of total energy requirements for a RT. Moreover, it cannot be added directly to our estimations for RES energy requirements for RT, as commented above, because the changes in infrastructures must be evaluated per sector and with a more precise calculation on how the required total energy will affect to a new energy system based mainly on RES. A more detailed analysis should be done to assess such issues, mainly calculating the net energy decay from all the fossil sources. Such calculations are out of the scope of the present work.

Focusing only in the oil liquids net energy decay we have considered maximum and minimum rates of deployment of RES for each model of EROI decline and, according to a scenario of total replacement of non-renewable sources by 100% RES in 25 years from now. The goal of this exercise provides an assessment of how much energy from all oil liquids should be addressed assuming that oil liquids are not replaced, but used as the main energy source to implement the RT. These estimations are necessary if the energy supply for transportation should be kept globally. We want to stress that our analysis assumes that such energy coming from oil and devoted to the transport is essential to be replaced and the more sustainable way to do it is by RES. It is worth to note that the practical implementation of such substitution is a more complex mater whose study is out of the scope of this work. These rough estimations give a maximum of 20% of the oil liquids total net energy by 2040 to be invested in RT in the worst case (Linear model). These results evidence that the RT is feasible in terms of available net energy, even in the most pessimistic scenario for maximum development rates. However, such amount of required energy implies huge economic and societal efforts.

On the other hand, the minimum development rates for RT are calculated assuming that RES must compensate the decline in net energy from all oil liquids under two hypothetical scenarios (constant level and 3% growth) and for the two extreme EROI decay models; the goal of this second exercise has been to assess the minimum rate of deployment of RES in order to avoid problems with the net energy supply at global scale. In the first case we show that the RT is achievable but, depending on the EROI decay finally taking place, may require in some periods to invest at least 10% and up to 20% of all oil net energy available per year, which may interfere with other uses of net energy by society. Those percentages would be considerably higher if the decay of conventional oil production is faster than what IEA expects, which is not implausible given the questionable IEA data processing shown in section 2. Regarding this second analysis, it shows that if we want to avoid problems with global net energy supply, the RT cannot wait for quite long, especially if a moderate increase in net energy supply (required to feed a healthy economy according to many economic models) is to be expected: if the equivalent of a growth of 3% in net energy from liquid hydrocarbons must be attained, new RES should be deployed at a rate of at least 4% annual disregarding the EROI model, and even reaching 8% during one of the periods in Linear (L) model. Those rather important rates of RES deployment, which are the required minimum to avoid problems with the global energy supply, get substantially increased as the RT is postponed, and they can go above 10% annual in just a decade from now. Our analysis of both, constant and 3% required growth in the global net energy can conduct to a short run reduction of the EROI within a long run stabilization or growth [75].

Other point that arises in such RT is that oil currently almost does not affect the electricity production and, as RES produce electricity, there are some minor impacts from Oil to the electricity generation. Here we argue that Oil liquids net energy decay will have strong impacts into the transportation system [76,59], since this sector consumes approximately 28% of total secondary energy, 92% of it in form of oil derivatives [14,77]. The current global economy requires an extensive and low price transportation system to keep the industrial and raw materials flows to allow and deploy the RES. This freight transportation relies basically in Oil. All this net energy demand will have to be supplied with renewable energy in a future post-oil economy. According to García-Olivares [59,76] a future post-carbon society could sustain a vehicles fleet similar to that we have currently (about 10^9 vehicles) if an intelligent restructuring of the transport were made. To manage the limited reserves of platinum-palladium, fuel cell motors should be reserved mainly for boats, ambulance, police and fire trucks, and by 10% of the present number of farm tractors. Other tractors should be powered by batteries or by connection to the electric grid, and similarly for other commercial trucks. This solution could be more easily implemented if land transport were based on electric trains for freight and passengers between cities and villages. Open field work in farming, mining and construction sometimes requires high power tractors that should also be supplied by fuel cell vehicles, while other generic farming work could be done using many smaller electric tractors which would recharge their batteries in the grid. Thus, full connection of farms to the electric grid would become necessary in the future economy. For similar reasons, any project involving open field construction will have to plan for the building of a connection to the grid. This reorganization of open-field work is a major challenge but does not necessarily create an insurmountable problem if there is political will to foster an energy transition. Then, the decay in net energy of Oil liquids has necessarily to be compensated with other energy sources, our work shows how this compensation is not only necessary for the RT to a post-carbon economy but also achievable if determinate and urgent policies are implemented. The policy implications of this RT will be discussed in the next section.

5. Conclusions

This work shows that the transition to a Renewable Energy Supply system has to be defined taking into account the EROI of available primary energy sources. The figures presented in this work should be taken as optimistic/conservative estimates about the needs for a future RT; actual required rates of deployment and energy needs can be significantly greater that those presented here if other factors are properly accounted.

5.1. Evolution of net energy for all oil liquids and their implication for RT

In this work we have just analyzed the situation regarding oil net energy, but the analysis should be extended to the rest of non-renewable sources: coal, natural gas and uranium, even though we expect their importance will be relatively lower in the particular energy sectors in which oil has high impact (i.e. transportation). We considered and initial estimation of the impacts of coal, gas and biofuels for transport sector but further analysis are required at this point. The work necessary for such detailed analysis is far beyond the scope of this paper.

The hypothesis that this work manage is try to keep the current energy production level (or to increase it) just replacing a non-renewable energy source by other (RES) which is more sustainable in terms of CO_2 emissions. Thus the main idea is to analyze if the fossil fuel based economy could be partially supported in the future by renewable energy sources. The deployment of RES will have a double effect: will fill the gap of the net energy coming from oil liquids and the need to keep/increase the energy production for a healthy economy and also help to reduce GHG emissions. But indeed conservation will be a crucial instrument in any viable RE transition. As an example, the Energy savings 2020 report of the European Union shows that 38% of energy could be saved in 2030 for the residential sector (relatively to a base case scenario) if a “high policy intensity” scenario of saving measures were implemented. For all final sectors this saving could be 29% of secondary energy relative to the base case [78].

Taking our estimates on the net energy future decay into account, we have shown how current and future net energy availability in terms of oil liquids can allow a renewable transition. The required minimum rates of RES development to fulfill the RT, are feasible considering that during the last 5-years the global mean RES development has been around the 5%, with 2012 having 8% growth (according the data in REN21 [79] report). These rates of RES development are also compatibles with the IEA forecasting of 5% RES mean growth for the next 5 years [80].

5.2. Necessary policies for the RT regarding oil liquids net energy

At this point, a question arises about how this necessary RT should be supported, particularly taking into account the development rates required to compensate the net energy decay of oil liquids. Such rates require a continuous investment support to keep the pace of RT. Many economists support some form of carbon fee, such as a revenue neutral carbon fee and dividend plan, as a market-based solution to the problem. The effort that has gone into promoting carbon fee plans is laudable, and carbon pricing is clearly one of the public policy levers that governments and regulators will need to use in the future. But a carbon tax alone will not probably solve the problem: (i) it will not move quickly enough to catalyze very specific, necessary changes, and (ii) a carbon fee and dividend system would have to be implemented on a global level, something that is hardly going to happen. Another possibility to obtain the necessary investment capital to support the RT is to develop financial instruments. Thus, instead on relying only in the public financing of the necessary changes and infrastructures, an additional support could come from private initiatives. For instance, a financial instrument currently in use is the Yield Cos, which allows private investors to participate in renewable energy without many of the risks associated with it. However, they have risks related to the payoff time of the investment within the regulatory framework that can influence it. Another related issue arises from the oscillations of the electricity price, which can affect the consumers costs, paying more for the electricity of their solar panels than they would for grid electricity.

Regardless on whether the investment is coming from private of public sectors what is clear from the numbers we are managing here is that a decisive effort from the policy side supporting the RT must not be avoided anymore. Particularly, in Europe, European Commission launched main plans or strategies to promote low-carbon socio-economy. One of them is the Strategic Energy Technology Plan [81], which aims to accelerate the development of low-carbon technologies and promotes research and innovation efforts to support EU's transformation in a low-carbon energy system. However, such plans act as a general framework for more concrete policy actions. The work developed here aims to give a set of values estimated under optimistic assumptions, to stimulate a debate, and also to warn about the future global net energy availability and the urgency of more concrete and determined policies at all administrative levels (region, country and international) to support and to enhance the implementation of RES.

5.3. Limitations and impacts of the RT

Finally, we cannot dismiss the side effect of the RT development produced by the stress and constraints on critical raw materials supply used in the implementation of RES as pointed out in several reports [82,83] and discussed in the literature (e.g. Ref. [9]; Davidson et al., 2014). As showed by recent analysis a negative feedback can be produced by the need of usual raw materials in wind power technologies and solar cell metals (Elshkaki and Graedel, 2014, 2015). Most of them are classified into rare earth elements that appear as byproducts of more common materials. The rate of RES implementation would imply more efforts to obtain raw materials and in turn to produce an excess of co-products having two negative impacts. First the oversupply of eventually unnecessary host products may lower its prices and then discouraging life recycling of those metals, a situation that presently has trapped the emerging economies strongly dependent on commodities but also the mining companies. A second negative feedback is the environmental impact associated to the extraction and processing of huge quantities of raw material, being translated in the best case into an increase of GHG emissions exceeding the benefits of the RT savings and in the worse cases into an increase of highly poisoning heavy metals and radioactive elements. This situation can only be surmounted by promoting research efforts to develop green technologies less dependent on such materials and by policies strongly encouraging material recycling.

Acknowledgements

We acknowledge the support of MEDEAS project through the funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.renene.2017.09.035.

References

[1] G7 and EU commitment. 2015. https://ec.europa.eu/energy/en/news/g7-countries-and-eu-underline-commitment-sustainable-energy-security.

[2] K. Riahi, D.P. Vuuren, E. Kriegler, J. Edmonds, B.C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J. Crespo Cuaresma, K.C. Shamir, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L.A. Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, M. Luderer Harmsen, H. Takahashi, L. Baumstark, J.C. Doelman, M.Z. Kainuma, G. Klimont Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau, M. Tavoni, The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview, Glob. Environ. Change 42 (2017) 153–168.

[3] M.Z. Jacobson, M.A. Delucchi, Providing all global energy with wind, water, and solar power, Part I: technologies, energy resources, quantities and areas of infrastructure, and materials, Energy Pol. 39 (2011) 1154–1169.

[4] T.A. Trainer, Critique of Jacobson and Delucchi's proposals for a world renewable energy supply, Energy Pol. 44 (2012) 476–481.

[5] S. Sgouridis, U. Bardi, D. Csala, A Net Energy-based Analysis for a Climate-constrained Sustainable Energy Transition, 2015. https://arxiv.org/abs/1503.06832.

[6] C. De Castro, M. Mediavilla, L.J. Miguel, F. Frechoso, Global wind power potential: physical and technological limits, Energy Pol. 39 (2011) 6677–6682.

[7] C. De Castro, M. Mediavilla, L.J. Miguel, F. Frechoso, Global solar electric potential: a review of their technical and sustainable limits, Renew. Sustain. Energy Rev. 28 (2013) 824–835.

[8] M.Z. Jacobson, C.L. Archer, Saturation wind power potential and its implications for wind energy, PNAS 109 (39) (2012) 15679–15684, https://doi.org/10.1073/pnas.1208993109.

[9] Ayman Elshkaki, T.E. Graedel, Solar cell metals and their hosts: a tale of oversupply and undersupply, Applied Energy 158 (2015) 167–177, https://doi.org/10.1016/j.apenergy.2015.08.066. ISSN: 0306-2619.

[10] Ayman Elshkaki, T.E. Graedel, Dysprosium, the balance problem, and wind power technology, Applied Energy 136 (2014) 548–559, https://doi.org/10.1016/j.apenergy.2014.09.064. ISSN: 0306-2619.

[11] R. Kleijn, E. van der Voet, Resource constraints in a hydrogen economy based on renewable energy sources: an exploration, Renew. Sustain. Energy Rev. 14 (2010) 2784–2795.

[12] E. Phil, D. Kushnir, B. Sanden, F. Johnsson, Material constraints for concentrating solar thermal power, Energy 44 (2012) 944–954.

[13] A. García-Olivares, J. Ballabrera-Poy, E. García-Ladona, A. Turiel, A global renewable mix with proven technologies and common materials, Energy Pol. 41 (2012) 561–574.

[14] A. Grubler, T.B. Johansson, L. Mundaca, N. Nakicenovic, S. Pachauri, K. Riahi, H.H. Rogner, L. Strupeit, Chapter 1:energy primer, in: Global Energy Assessment—toward a Sustainable Future, Cambridge University Press, Cambridge, UK; New York, NY, USA, 2012, pp. 99–150. The International Institute for Applied Systems Analysis: Laxenburg, Austria.

[15] C. Shaw, Hales Simon, P. Howden-Chapman, R. Edwards, Health co-benefits of climate change mitigation policies in the transport sector, Nat. Clim. Change 4 (2014) 427–433, https://doi.org/10.1038/nclimate224.

[16] C.J. Cleveland, Energy transitions past and future, in: Cutler.J. Cleveland (Ed.), Encyclopedia of Earth, Environmental Informat, Washington, DC, 2008. http://www.eoearth.org/article/Energy_transitions_past_and_future.

[17] N. Gagnon, C.A.S. Hall, L. Brinker, A preliminary investigation of the energy return on energy invested for global oil and gas extraction, Energies 2 (2009) 490–503, https://doi.org/10.3390/en20300490.

[18] S. Sorrell, R. Miller, R. Bentley, J. Speirs, Oil futures: a comparison of global supply forecasts, Energy Policy 38 (2010) 4990–5003.

[19] A.R. Brandt, Review of mathematical models of future oil supply: historical overview and synthesizing critique, Energy 35 (9) (2010) 3958–3974.

[20] S.P.A. Brown, J. Darmstadter, Energy and natural resources, in: Megatrends in Global Interaction, first ed., Bertelsmann Foundation, Bertelsmann Stiftung, Gütersloh, Germany, 2012.

[21] R. Rapier, Peak Oil Has More to Do with Oil Prices than You May Think. Oil Price, 2015. http://oilprice.com/Energy/Oil-Prices/Peak-Oil-Has-More-To-Do-With-Oil-Prices-Than-You-May-Think.html.

[22] P. Berg, A. Boland, Nat. Resour. Res. 23 (2014) 141, https://doi.org/10.1007/s11053-013-9207-7.

[23] M.C. Guilford, C.A.S. Hall, P. O'Connor, C.J. Cleveland, A new long term assessment of energy return on investment (EROI) for U.S. oil and gas discovery and production, Sustainability 3 (2011) 1866–1887, https://doi.org/10.3390/su3101866.

[24] R.H. Williams, E.D. Larson, A comparison of direct and indirect liquefaction technologies for making fluid fuels from coal, Energy Sustain. Dev. 7 (2003) 103–129.

[25] R. Heinberg, D. Frindley, The end of cheap coal, Nature 468 (7322) (2010) 367–369. ISSN: 0028-0836.

[26] M. Höök, W. Zittelb, J. Schindlerb, K. Alekletta, Global coal production outlooks based on a logistic model, Fuel 89 (2010) 3546–3558.

[27] T.W. Patzek, G.D. Croft, Energy 35 (2010) 3109–3122.

[28] A.R. Farrell, A.R. Brandt, Risks of the oil transition, Environ. Res. Lett. 1 (2006) 6, 014004.

[29] R.W. Howarth, A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas, Energy Sci. Eng. 2 (2) (2014) 47–60.

[30] IRENA, The True Cost of Fossil Fuels: Saving on The Externalities of air Pollution and Climate Change, 2016.

[31] C. Kerschner, C. Prell, K. Feng, K. Hubacek, Glob. Environ. Change 23 (6) (2013) 1424–1433, https://doi.org/10.1016/j.gloenvcha.2013.08.015, 2013.

[32] R.K. Kauffman, L.D. Shiers, Alternatives to conventional crude oil: when, how quickly, and market driven? Ecol. Econ. 67 (2008) 405–411.

[33] A. García-Olivares, J. Ballabrera-Poy, Energy and mineral peaks, and a future steady state economy, Technol. Forecast. Soc. Change 90 (Part B) (2015) 587–598, https://doi.org/10.1016/j.techfore.2014.02.013. ISSN: 0040-1625.

[34] M.K. Heun, M. de Wit, Energy return on (energy) invested (EROI), oil prices and energy transitions, Energy Pol. 40 (2012) 147–158.

[35] D.J. Murphy, The implications of the declining energy return on investment of oil production, Phil. Trans. R. Soc. A 372 (2014), 20130126, https://doi.org/10.1098/rsta.2013.0126.

[36] C.A.S. Hall, Migration and metabolism in a temperate stream ecosystem,

Ecology 53 (1972) 585–604.

[37] H.T. Odum, Environment, Power, and Society, Wiley, New York, NY, 1971.

[38] M. Dale, S. Krumdieck, P.A. Bodger, Dynamic function for energy return on investment, Sustainability 3 (10) (2011) 1972–1985.

[39] C.A.S. Hall, Maximum Power: the Ideas and Applications of H.T. Odum, University Press Colorado, 1995.

[40] C.J. Cleveland, Energy quality and energy surplus in the extraction of fossil fuels in the U.S, Ecol. Econ. 6 (1992) 139–162.

[41] C.A.S. Hall, R. Powers, W. Schoenberg, Peak oil, EROI, investments and the economy in an uncertain future, in: D. Pimentel (Ed.), Biofuels, Solar and Wind as Renewable Energy Systems: Benefits and Risks, Springer Science, The Netherlands, 2008, pp. 109–132.

[42] C.A.S. Hall, S. Balogh, D.J.R. Murphy, What is the minimum EROI that a sustainable society must have? Energies 2 (2009) 25–47.

[43] WEO, 2014. http://www.worldenergyoutlook.org/publications/weo-2014/

[44] WEO, 2012. http://www.worldenergyoutlook.org/publications/weo-2012/

[45] D.A. Pittam, G. Pilcher, Measurements of heats of combustion by flame calorimetry. Part 8.—methane, ethane, propane, n-butane and 2-methylpropane, J. Chem. Soc. 68 (1972) 2224. Faraday Transactions 1: Physical Chemistry in Condensed Phases.

[46] A. García-Olivares, A. Turiel, The second half of the fossil fuel age: environmental externalities, net energy and energy security concerns, in: R. Kumar (Ed.), Fossil fuels, Sources, Environmental Concerns and Waste Management Practices. NewYork: Ed.Nova, 2013.

[47] Glanfield, Energy Required to Produce Petroleum Products from Oil Sand versus Other Petroleum Sources, 2002. Ph.D. thesis (MIT).

[48] API, American Petroleum Institute, API Manual of Petroleum Measurement Standards, Chapter 11.1,vol XI/XII, Adjunct to: ASTM D1250-80 and IP 200/80, 1980.

[49] M. Humphries, North American Oil Sands: History Developments, Prospects for the Future, 2008. CRS report for congress).

[50] M.R. Gray, Upgrading Oil Sands Bitumen and Heavy Oil, University of Alberta Press, 2015.

[51] J. Laherrere, Oil & Gas Production Forecasts 1900-2100, 2013. http://forum.tribune-pic-petrolier.org/t382-articles-de-jean-laherrere-fevrier-2013-previsions-1900-2100-et-productions-iocs-et-previsions.

[52] B. Etemad, J. Luciani, World Energy Production 1800 – 1985, LibrairieDroz, Geneve, 1981. ISBN 2-600-56007-6.

[53] E. Thompson, S. Sorrell, J. Speirs, UKERC Review of Evidence on Global Oil Depletion. Technical Report 2: Definition and Interpretation of Reserve Estimates, UK Energy Research Centre, 2009. UKERC/WP/TPA/2009/017.

[54] J. Laherrère, Fossil fuels: what Future? Workshop “Global Dialogue on Energy Security”, the Dialogue International Policy Institute, China Institute of International Studies, 2007. http://hubbertpeak.com/laherrere/Beijing20061009.pdf.

[55] US Department of the Interior, U.S. Geological Survey World Petroleum Assessment, U.S. Geological Survey, 2000. http://pubs.usgs.gov/dds/dds-060/.

[56] C.A.S. Hall, J.G. Lambert, S.B. Balogh, EROI of different fuels and the implications for society, Energy Pol. 64 (2014) 141–152, https://doi.org/10.1016/j.enpol.2013.05.049.

[57] D. Hughes, Drill, Baby, Drill: Can Unconventional Fuels Usher in a New Era of Energy Abundance? February 19, Post Carbon Institute, 2013.

[58] D. García, A New World Model Including Energy and Climate Change Data, First International Workshop “Mission Earth-modeling and Simulation for a Sustainable Future”, AGSME, Zurich, Switzerland, 2009. January 2009, http://europe.theoildrum.com/node/5145. (Accessed 13 June 2013).

[59] A. Garcia-Olivares, Substitutability of electricity and Renewable materials for fossil fuels in a Post-Carbon Economy, Energies 8 (12) (2015b) 13308–13343.

[60] M.A. Delucchi, M.Z. Jacobson, Providing all global energy with wind, water, and solar power, Part II: technologies, energy resources, quantities and areas of infrastructure, and materials, Energy Pol. 39 (2011) 1170–1190.

[61] F. Trieb, C. Schillings, T. Pregger, M. O'Sullivan, Solar electricity imports from the Middle East and north africa to Europe, Energy Pol. 42 (2012) 341–353.

[62] UN, United Nations, Department of Social Affairs, World Population to 2300, ST/ESA/SER.A/236, United Nations, New York, 2004.

[63] R. Banerjee, Y. Cong, D. Gielen, G. Jannuzzi, F. Maréchal, A.T. McKane, M.A. Rosen, D. van Esand, E. Worrell, Chapter 8-energy end use: industry, in: Global Energy Assessment - toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY,, 2012, pp. 513–574. USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

[64] USGS, US Geological Survey. Commodity Statistics and Information, 2015. Iron and Steelhttp://minerals.usgs.gov/minerals/pubs/commodity/.

[65] USDOE, Natural Gas for Cars. Using Natural Gas for Vehicles: Comparing Three Technologies, US Departmet of Energy- Energy Efficiency and renewable Energy, 2015. DOE/GO-102015–104685, December 2015.

[66] A. Huss, H. Maas, H. Hass, Ank-to-wheels Report Version 4.0. JEC Well-to-wheels Analysis. European Commission. EUR-scientific and Technical Research Series, 2013, https://doi.org/10.2788/40409.

[67] G.L. Basso, B. Nastasi, D. Astiaso Garcia, F. Cumo, How to handle the Hydrogen enriched Natural Gas blends in combustion efficiency measurement procedure of conventional and condensing boilers, Energy. ISSN: 0360-5442 123 (15) (March 2017) 615–636, https://doi.org/10.1016/j.energy.2017.02.042.

[68] S. Pellegrino, A. Lanzini, P. Leone, Greening the gas network – the need for modelling the distributed injection of alternative fuels, Renew. Sustain. Energy Rev. ISSN: 1364-0321 70 (April 2017) 266–286, https://doi.org/10.1016/j.rser.2016.11.243.

[69] P. Rotunno, A. Lanzini, P. Leone, Energy and economic analysis of a water scrubbing based biogas upgrading process for biomethane injection into the gas grid or use as transportation fuel, Renew. Energy. ISSN: 0960-1481 102 (Part B) (March 2017) 417–432. https://doi.org/10.1016/j.renene.2016.10.062.

[70] World Energy Council report. (2013). Available : https://www.worldenergy.org/publications/2013/world-energy-scenarios-composing-energy-futures-to-2050/

[71] T. Pootakham, A. Kumar, A comparison of pipeline versus truck transport of bio-oil, Bioresour. Technol. ISSN: 0960-8524 101 (1) (January 2010) 414–421. https://doi.org/10.1016/j.biortech.2009.07.077.

[72] T. Pootakham, A. Kumar, Bio-oil transport by pipeline: a techno-economic assessment, Bioresour. Technol. ISSN: 0960-8524 101 (18) (September 2010) 7137–7143. https://doi.org/10.1016/j.biortech.2010.03.136.

[73] US EIA, US Energy Information Administration. International Energy Statistics, 2014. http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm.

[74] Mark Z. Jacobson, A. Delucchi Mark, Bazouin Guillaume, A.F. Bauer Zack, C. Heavey Christa, Fisher Emma, Sean B. Morris, J.Y. Piekutowski Diniana, A. Vencill Taylor, W. Yeskoo Tim, Energy Environ. Sci. 8 (2015) 2093.

[75] J.R. Gever, R. Kaufmann, D. Skole, C. Vorsmarty, Beyond Oil: the Threat to Food and Fuel in the Coming Decades, Ballinger Press, Cambridge, MA, 1986.

[76] García-Olivares, A. Substituting Silver in Solar Photovoltaics Is Feasible and Allows for Decentralization in Smart Regional Grids, Environmental Innovation and Societal Transitions. ISSN: 2210-4224, 2015, https://doi.org/10.1016/j.eist.2015.05.004. Available online 5 June.

[77] U.S. Energy Information Administration, Monthly Energy Review, March 2015. Tables 1.3, 2.1–2.6.

[78] B. Wesselink, Robert Harmsen, Wolfgang Eichhammer, Energy SAVINGS 2020 – How to Triple the Impact of Energy Saving Policies in Europe. European Climate Foundation (ECF) and the Regulatory Assistance Project (RAP), Commission of the European Union, 2010.

[79] REN21, Renewables 2014: Global Status Report (PDF), 2014.

[80] IEA, Medium-term Renewable Energy Market Report 2014, 2014. Available online at:http://www.iea.org/bookshop/480-Medium-Term_Renewable_Energy_Market_Report_2014.

[81] SET-Plan. European Commission.: http://ec.europa.eu/energy/en/topics/technology-and-innovation/strategic-energy-technology-plan

[82] European Commission, Critical Raw Materials for the EU: Report of the Ad Hoc Working Group on Defining Critical Raw Materials, European Commission, Brussels, 2014.

[83] US Department of Energy, Critical Materials Strategy, 2011. https://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf.