Peak oil and the low-carbon energy transition: A net-energy perspective

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Graphical Abstract

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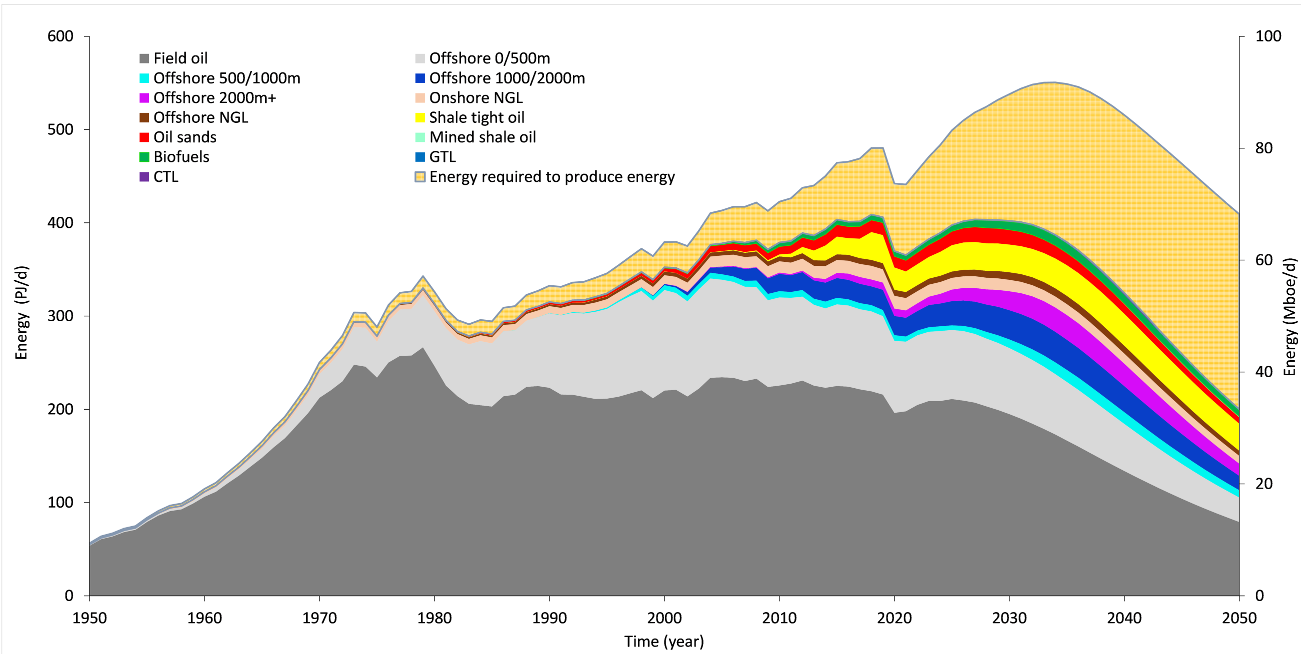

Highlights

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- Global gross and net-energy of oil liquids production is determined from 1950 to 2050.
- Energy required for production is estimated to be 15.5% of the actual gross energy.
- Oil liquids become a limit to a rapid and global low-carbon energy transition.
- The peak supply vs. peak demand dispute needs to be re-examined.
- Focus should be put instead on net-energy transition and wise energy consumption.

Peak oil and the low-carbon energy transition: a net-energy perspective

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Abstract

Since the Pennsylvania oil rush of 1859, petroleum has quickly become the dominant fuel of industrial society. The "Peak Oil" debate focused on whether or not there was an impending production crunch of cheap oil, and whilst there have been no shortages across the globe, a shift from conventional to unconventional oil liquids has occurred. One aspect of this shift was not fully explored in previous discussions–although of some importance in a low-carbon energy transition context: the extent to which the net-energy supply of oil products will be affected by the use of lower quality energy sources. To fill this gap, this paper incorporates standard EROI (energy-return-on-investment) estimates and dynamic decline functions in the GlobalShift all-liquids bottom-up model on a global scale. We determine the energy necessary for the production of oil liquids (including direct and indirect energy costs) to represent today 15.5% of the energy production of oil liquids, and growing at an exponential rate: by 2050, a proportion equivalent to half of the gross energy output will be engulfed in its own production. Our findings thus question the feasibility of a global and fast low-carbon energy transition. We therefore suggest an urgent return of the peak oil debate, but including net-energy issues and avoiding a narrow focus on 'peak supply' vs 'peak demand'.

1. Introduction

Today, oil is a critical supply chain component for 90% of all industrially manufactured products (Michaux, 2020); as such, it is the backbone of industrial civilization. Its large range of strategic advantages (liquid state, high energy density, numerous applications, etc.) have driven its ever-escalating search and use during the past century. This gargantuan intake not only leveraged our societal development as efficient and powerful machines–conceptualized as energy slaves by Fuller (1940)–were continuously added to the total workforce, but also generated a thirst for oil. The 'black gold' now represents one third of the world's primary energy consumption (BP, 2020). At the interface of geopolitical, economic, social and climatic challenges, oil is essential to the globalized world but in the meantime endangers the planet's life supporting functions: this is the oil paradox (Sandalow, 2007). Yet, another worrying risk has raised concerns due to the non-renewable nature of oil: its possible contraction as a cheaply extractable energy source which could mark a civilization transformation (Holdren, 2006).

Such a possibility was the subject of an intense discussion during the 2000s, but has since lost academic and political interest. It is in part due to the shale revolution that led the United States to a new all-time production record. The debate seemed closed until the International Energy Agency (IEA) warned in 2018 of the likelihood of a coming production crunch (IEA, 2018), previously glimpsed at by Fustier et al. (2016). The Coronavirus oil consumption plunge and the subsequent oil prices war between Saudi Arabia and Russia have now put this issue back on the agenda, notably for regions dependent on oil imports such as the EU (The Shift Project, 2020, 2021). As a matter of fact, the number of organizations who envisage global oil demand to peak in the next ten to fifteen years has kept on growing to include energy research groups (Bernstein Energy, BloombergNEF), consulting firms (McKinsey), oil majors (BP, Equinor, Total) and oil intelligence companies (Rystad Energy, GlobalShift, Wood Mackenzie) (Tupaz, 2020).

However, forecasts have for long been confined to a gross energy view and paid little attention to the net-energy, i.e. the energy available after accounting for the cost of its acquisition, usually inclusive of extraction, refinement and delivery. Sticking to the sole gross energy perspective becomes preoccupying as unconventional[1] oil liquids are continuously replacing higher quality conventional ones, and an energy-intensive transition to low-carbon energy sources is needed. However, the fact that changes in resource quality affect the long-term amount of net-energy of oil liquids at global scale has only be discussed and partially been analyzed (the relevant literature is reviewed in Section 3). This study attempts to explore this question and fill the literature gap that exists today. To do so, this article incorporates standard EROI (energy-return-on-investment: ratio of usable energy acquired from a given source of energy to the amount of energy expended to obtain that energy) estimates and dynamic decline functions in the GlobalShift all-liquids bottom-up model at global scale, from 1950 to 2050.

This paper is structured as follows. Section 2 retraces the peak oil debate history, setting the political and scientific aspects of the dispute. Section 3 describes the chosen Energy

[1]The oil industry identifies two categories of hydrocarbon deposits: conventional and unconventional resources. The distinction between the two types is rooted in the difficulty in extracting and producing the resource, however, there is no consensus as where to draw the line between the two, as it depends on either economic or geological issues (Graefe, 2009).

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Analysis (EA) perspective, the developed methodology and the data used. Section 4 presents the results, section 5 discusses them and section 6 draws conclusions.

2. Literature review

On the 8th of March 1956, Shell geophysicist Marion King Hubbert presented the results of his latest research at the spring meeting of the Southern District of the American Petroleum Institute (API) in San Antonio, Texas. By compiling past discoveries, production levels and future discovery predictions of the 48 U.S. lower states (excluding Alaska and Hawaii), Hubbert modeled the country's conventional oil production as a bell-shaped curve with the intuition that if individual fields follow such trends, the aggregation at a larger scale from an individual region to the planet as a whole, would produce a similar type of curve (Hubbert, 1956). His results led Hubbert to claim that the country was nearing the extraction of half of its recoverable petroleum resources and that the maximum production level or 'peak' would occur within a few years given the estimate made for the reserves: 1965 for 150 billion barrels and 1970 for 200. More importantly, he warned that the after-peak period would see a permanent decrease of about 5–10% a year.

This position was in contrast to the common belief in cheap oil abundance shared by his contemporaries and would not go without creating conflict, as portrayed by the intense confrontation with USGS (United States Geological Survey) director Vincent McKelvey (Priest, 2014). As years passed, the statistical verification of Hubbert's claims made his theory gain recognition: oil production in the lower 48 states did reached its height in 1970 and declined each year thereafter[2]. The 1970s energy crisis–symbolized by 1973 and 1979 oil crises–pushed the debate into the public domain. Galvanized by his work and strong personality, believers in the peak theory saw in Hubbert a prominent father-like figure (Inman, 2016) whose technocratic political ties exacerbated attention to the debate (Hemmingsen, 2010). It led to a point where the dispute can be seen as the first block of the modern discussion on resources scarcity breached by the Club of Rome "Limits to Growth" report of Meadows et al. (1972) (Hall and Day, 2009). As a result of the general optimism following the collapse in oil prices after the 1980s OPEC quota war, cheap oil production's fate has slowly been put aside. It is only when two long-time oil experts, Colin Campbell and Jean Laherrère, published in 1998 "The End of Cheap Oil" that this issue was brought back on the agenda (Campbell and Laherrère, 1998).

Campbell and Laherrère relied on Hubbert's work and on the PetroConsultants (now IHS Markit) dataset to update the curves on a global scale and warned about the coming peak for conventional oils expecting it to take place around 2005. The term "peak oil"[3] was latter coined by Colin Campbell in 2000 and popularized in 2001 as the Association for the Study of Peak Oil and Gas (ASPO) was established with the purpose raise the issue of cheap oil future scarcity. The formation of a dedicated entity, the statistical validation of their claim[4] combined with the 2007-08 financial crisis– expected to partly result from the oil production incapability to increase (Hamilton, 2012)–exposed once again the question of cheap oil production decline to the world. Books were published[5], bets were placed, documentaries were screened and articles flourished in scientific journals and on specialized websites such as the now defunct "TheOilDrum" forum to altogether form a vibrant community (Campbell, 2003; Bridge, 2010; Campbell, 2012). Governments themselves seized the matter in a direct–the Belgian Walloon parliament created a "peak oil committee"–or indirect form–reports were commissioned by the British Department of Energy in concert with the Bank of England and the Department of Defense (Michaux, 2020), as well as the U.S. Department of Energy (Hirsch, 2007). Military affiliated institutions, for instance in the U.S. (Parthemore and Nagl, 2010) or Germany (BTC, 2010), and private industries (e.g. the U.K. Industry Task-Force on Peak Oil and Energy Security) also took on the issue.

Oil production models have come to dominate the debate as stakeholders were engaged in a race to guess the peak date. Modeling techniques became the epicenter of the attention[6] and a myriad of forecasts appeared, ranging from short-term peak, a plateau with possible undulations to long-term or no peak (Sorrell et al., 2010a; Brandt, 2010; Hughes and Rudolph, 2011; Foucher, 2013; Chapman, 2014; Jackson and Smith, 2014; Andrews and Udall, 2015). At some point, it became clear to number of experts that the time of cheap abundant oil–coined as the first half of the age of oil by Campbell (2015b)–was coming to an end (Greene, Hopson and Li, 2006; Bentley and Boyle, 2008; Salameh, 2008; Rhodes, 2008; Tsoskounoglou, Ayerides and Tritopoulou, 2008; Kjärstad and Johnsson, 2009; Sorrell et al., 2009, 2010b, 2012; Criqui, 2013). Yet, the debate was still raging as misconceptions on oil formation (Tsatskin and Balaban, 2008; Höök et al., 2010), the proper definition and use of reserves (Bentley, Mannan and Wheeler, 2007; Campbell and Gilbert, 2017), the economic aspect of oil (Watkins, 2006; Bentley, 2016), the difference between flow and stock notions (Jakobsson et al., 2012), the variability in ultimate recoverable resources estimates (McGlade, 2012) or even the statistical definition of peak oil (Warrilow, 2015) obscured the discussion and created a certain cacophony. These confusions polarized the debate between two radical camps[7]:

[2] If the 1970 peak magnitude was nearly 20 percent above Hubbert's high peak prediction, the trends soon caught up with the forecast and only started to drift apart in the early 2000's.

[3] Peak oil designates the theorized point in time when the maximum rate of extraction of petroleum is reached.

[4] The IEA 2010, 2012 and 2018 reports conceded that the conventional oil peak occurred around 2005-2008 (IEA, 2010, 2012, 2018).

[5] Among others: Goodstein (2004); Heinberg (2005); Simmons (2006); Clarke (2009); Deffeyes (2009); Ruppert and Campbell (2010).

[6] This sub-debate is still active today. See: Houthakker (2002); Cavallo (2004); Brandt (2007); Holland (2008); Brandt (2010); Reynes, Okullo and Hofkes (2010); Giraud (2011); Reynolds and Baek (2012); Brecha (2012); Smith (2012); Wang and Feng (2016); Peebles (2017); Jones and Willms (2018); Reynolds (2020).

[7] Reducing the peak oil debate to two opposing sides is misleading: a wide spectrum of positions has been observed which can more realistically

late or no peak advocates and early peak defenders (so called "peak-oilers") (Chapman, 2014). The latter were cartooned as prophets of doom, Cassandras, catastrophists, fantasists or "chimeras without substance" (Maugeri, 2004; Smil, 2006; Radetzki, 2010; Mann, 2015; Tracy, 2016) though some arguments of the critics have been demonstrated as fallacious (Meng and Bentley, 2008; Brecha, 2013). This however, did not prevent some projections from being too pessimistic. Personal convictions held an important place in the debate too as the discussion was flooded with political ties, private interests and data retention (Bardi, 2009; Atkinson, 2010). Unprecedented clashes took place which meant that–intentionally or not– the two groups did not find common ground to communicate effectively, possibly also due to the challenges surrounding the 'black gold' or the dramatic scenarios once evoked. It altogether hampered the sound development of a systemic political debate (Hemmingsen, 2010; Becken, 2014), which could have tremendous effects if cheap oil production peaks before our society is prepared for it (Hanlon and McCartney, 2008; Frumkin, Hess and Vindigni, 2009; Curtis, 2009; Korowicz, 2010; Woods et al., 2010; de Almeida and Silva, 2011; Neff et al., 2011; Murphy and Hall, 2011a,b; Lutz, Lehr and Wiebe, 2012; Tverberg, 2012; Bentley, Mushalik and Wang, 2020).

Accelerating in the 2010s, the Shale Revolution –i.e. the production of oil from unconventional resources and especially American tight oil–marked a turning point in the debate in addition to having crucial economic and geopolitical consequences at the global scale (Auping et al., 2016). Such a production boom can be explained by a unique[8] and fertile environment: important resources, an hydrocarbon policy which allows the land-owner to possess what lies underneath his estate, a large infrastructure network facilitating the oil and gas sectors expansion, the most important fleet of rigs in the world, the possibility to quickly train qualified oil engineers (thanks to more than one hundred years of practice), direct access to the biggest market worldwide and the connection to an unbridled speculative debt system. Furthermore, it was facilitated by specific triggering components: financial regulations prompted oil majors to invest in shale companies[9], progress made in horizontal drilling and hydraulic fracturing technologies was significant (Aguilera and Radetzki, 2013; Kim and Lee, 2020) and the shale gas industry was heavily supported by the government for the U.S. to become once again energy self-sufficient (Trembath et al., 2012; Maugeri, 2013; Wang and Krupnick, 2013; Reynolds and Umekwe, 2019). If this boom longevity was questioned since its onset (Hugues, 2013, 2014; Heinberg, 2014), oil production curves still diverged from existing projections, partly because unconventional oil supplies were not previously considered as a viable mitigation strategy and thus were not included in the projections of oil availability (de Castro, Miguel and Mediavilla, 2009; Brecha, 2012).

What appeared as a statistical invalidation of peak oil without being strictly so[10], marked a gradual quietening of the debate, symbolized by TheOilDrum closure in 2013, the drop in influence of ASPO, and the reduction in references to this issue in the scientific and public spheres. This loss of interest was furthermore amplified by a number of factors: the loss of famous peak oilers (Matthew Simmons, C. Michael Ruppert, Kenneth S. Deffeyes, etc.), the presence of few extreme positions (Schneider-Mayerson, 2015), an absence of political proposals, a focus on climate change regulation and a fundamental "clash of absolutes" with the mainstream belief in abundance and unlimited technological progress (Bardi, 2019). The establishment of a dedicated journal in 2015 (The Oil Age, terminated in 2017) and a special issue outlined in the Philosophical Transactions of the Royal Society (Miller and Sorrell, 2014) failed to turn the tide: the peak oil debate shrank to its core authors. The last books (to date) of famous peak oilers (Aleklett, 2012; Campbell, 2013; Bentley, 2016), aiming to provide the next generation with strong scientific grounds for peak oil theory and debate, had finally come to look like a swan song. And while a raft of modelers raised the issue of net-energy reduction due to the transition in quality from conventional to unconventional oil liquids, they were in majority mocked by the public and their work qualified as "overlooked myth" (Lacalle, 2011) or "a nonsense" (Worstall, 2011). This rejection further degraded the scientific relevance of peak oil in the eyes of the public at large and amplified the split with energy scientists who detected in net-energy decrease a real and under-recognized risk (Kreps, 2020; The Pivot Group, 2021).

The mid 2010s finally saw the emergence of the "peak demand" hypothesis which argues that peak oil will be driven by technological developments and policies of carbon dioxide emissions reduction (Kjärstad and Johnsson, 2009; Verbruggen and Marchohi, 2010; Verbruggen and de Graaf, 2013; Höök and Tang, 2013; Dale and Fattouh, 2018). However, the resource-limited peak theory has recently regained importance as the ability of the tight oil industry to double or triple its production (seen as a vital constraint to avoid a supply crunch by 2025 by the IEA in 2018) has been questioned based on economic and geological arguments (Fustier et al., 2016; Rhodes, 2017; Hacquard, Simoën and Hache, 2019; Hugues, 2019). Moreover, the 2020 Coronavirus oil consumption plunge and subsequent price war between Saudi Arabia and Russia have strongly undermined the industry capability to quickly recover pre-crisis production levels (Laherrère, 2020b; Nicola et al.,

be attributed to five groups: extreme optimist, optimist, moderate, pessimist, and extreme pessimist (Long, 2018).

[8]The Shale Revolution seems difficult to replicate elsewhere, at least with a similar pace and magnitude (Salameh, 2013; Saussay, 2018; Salygin et al., 2019).

[9]By extending the definition of reserves in 2010, the American Securities and Exchange Commission (SEC) allowed shale companies to overestimate their reserves, making them attractive for major companies (Exxon, Total, Equinor, CNOOC, etc.) that were lacking new discoveries to compensate for their production (Hall and Ramírez-Pascualli, 2013).

[10]It is postulated that there can be several 'resource-limited' production maxima of a field or region (Bentley, 2016), leading to model energy sources production through the Multicyclic Hubbert curve or "cycle jumping" technique at global (Nashawi, Malallah and Al-Bisharah, 2010; Wang et al., 2011; Maggio and Cacciola, 2012) or regional scales (Ebrahimi and Ghasabani, 2015; Wang et al., 2016) with varying accuracy (Anderson and Conder, 2011; Tunnell et al., 2020).

2020). The issue of net-energy from oil liquids in a context of transition to low-carbon energy sources seems thus timely and definitely requires more urgent attention than it currently receives.

3. Materials and methods

Energy analysis (EA) places the finiteness of the Earth's resources at the heart of its approach. It holds its roots in biophysical economics that sees human societies as thermodynamic or metabolic dissipative systems collecting high quality primary energy before converting it in-part as useful energy and rejecting the rest as low-quality energy in the surrounding environment (Georgescu-Roegen, 1971; Odum, 1971; Daly, 1977; Cleveland et al., 1984). Societies evolve and become more complex, thus requiring more and more energy[11] which in turn drives complexity growth and so on (Tainter, 1988). EA distinguishes two problems that arise from this way of working. The first is the finite stock of available energy sources: energy extraction rates first grow, reach a peak (precluding further growth driven by this energy source) and decrease, making it in fact a flow issue. The second is the quality of the energy sources, as "humans like most other biological organisms use the highest quality, richest and easiest to obtain resources first" (Martenson, 2014), a concept also known as the "First Best Principle". Both effects combine meaning that at some point societies face diminishing energy sources returns that push them into an even greater energy quest[12] which, if not fulfilled, can potentially lead them to societal "collapses" characterized by a complexity drop[13]. Economic growth and comfort are not only questioned by lower qualitative and quantitative energy inputs (Ayres and Warr, 2009; Kümmel, 2011; Ayres and Voudouris, 2014; Smil, 2018) but the entire globalized civilization in its present form is at risk of first-order structural perturbations, some of which possibly coming from adverse effects due to induced environmental degradation as climate change. From this perspective, we argue that the one way to perceive systemic risks is to see these through the net- energy prism[14].

Coined in the early 1970s, a derived conceptual framework of the EA discipline known as the Net-Energy Analysis (NEA) allows us to characterize to what extent an energy source constitutes a net-source or a sink for society given the amount of energy required to obtain and deliver useful energy (Murphy, 2014). In other terms, it assesses the energy surplus (also called net-energy gain or NEG) of an energy source, if any. To do so, the NEA firstly sets the boundaries of the studied system, computes the energy provided by the resource at the final stage boundary and subtracts the required energy to make it happen. The NEA methodology translates into:

$$\text{Net energy} = \text{Gross energy} - \text{Energy req. to deliver energy} \tag{1}$$

The energy required to deliver energy can be constructed using net-energy indicators, of which a large array exists (Brandt and Dale, 2011; Rana et al., 2020). The most widely known and used is the energy return on (energy) investment EROI or ERoEI (Hall, 1972), which can be understood as:

$$\text{EROI} = \frac{\text{Energy delivered}}{\text{Energy req. to deliver energy}} \tag{2}$$

Assuming the energy delivered equals the gross energy:

$$\text{Net energy} = \text{Gross energy} \times \left(1 - \frac{1}{\text{EROI}}\right) \tag{3}$$

Despite the equations being simple and conceptually elegant, they have proved to be at the source of theoretical and practical difficulties, and EROI in particular is a controversial concept (Hall, 2017). Nevertheless, EROI estimates have been carried out along the years from numerous authors all coming to the same conclusion: unconventional fossil fuel EROI are lower than conventional ones, themselves declining (Murphy and Hall, 2010; Gupta and Hall, 2011; Dale, Krumdieck and Bodger, 2012; Hall, Lambert and Balogh, 2014; Murphy, 2014; Hall, 2016).

If Hubbert was the first to point out the importance of self-use energy for future global oil supply[15], Murphy (2009) has been the first to conceptualize it under the umbrella of a net Hubbert curve as a back-of-the-envelope calculation. Soon afterwards, Gagnon, Hall and Brinker (2009) assessed for the first time the global oil and gas EROI at the wellhead between 1992 and 2006, based on estimates of energy inputs derived from monetary expenditures of publicly traded companies. After theorizing dynamic functions for EROI (including extraction and processing) (Dale, Krumdieck and Bodger, 2011a), Dale, Krumdieck and Bodger (2011b) applied EROI estimates and the previously-mentioned decline functions to different past and future projections for conventional oil. Bentley (2015) has later taken up the subject as a tutorial exercise for students. Campbell (2015a) also incorporated net-energy ratios in his oil and gas forecast

[11] From this point of view, the society is an "exo-somatic metabolism" which along its evolution, moves off a hunter-gatherer system to let the share of its overall energy consumption required for non-primary biological needs (i.e., for its exo-somatic metabolism) grow in comparison to the share used for the primary biological needs of its people (i.e., for its endo-somatic metabolism) (Raugei and Leccisi, 2016).

[12] This process is sometimes referred to as the Red Queen effect (Van Valen, 1973; Giraud, 2019), who in Lewis Carroll's "Alice's Adventures in Wonderland" sequel "Through the Looking-Glass" explains to Alice that the faster they run, the more they will need in the coming second to run even faster to stay put.

[13] We follow Tainter's definition of collapse, but the definition of collapse varies from author to author (Middleton, 2019).

[14] Strictly speaking, "net-energy" also encompasses the net-energy per unit time i.e. the net-power prism (Odum, 1973; Hall and Klitgaard, 2011).

[15] "However, there is a different and more fundamental cost [to oil production] that is independent of monetary price. That is the energy cost of exploration and production. So long as oil is used as a source of energy, when the energy cost of recovering a barrel of oil becomes greater than the energy content of the oil, production will cease no matter what the monetary price may be." (Hubbert, 1982).

model while acknowledging that "input data are far from reliable and there are many places where estimates–and even guesses–are needed", which could be explained by the lower amount of reliable EROI studies and data at that time. On a global level but with a selected pool of oilfields, Brandt et al. (2015) determined static net-energy returns through an engineering-based model. In the same vein, Tripathi and Brandt (2017) and Masnadi and Brandt (2017) analyzed historical trends of energetic productivity respectively for five large and twenty five super-giant oil fields. Modifying Dale, Krumdieck and Bodger (2011a) dynamic functions, Court and Fizaine (2017) estimated the long-term EROI estimates for coal, oil, and gas global productions but were not interested in net-energy projections. Solé et al. (2018) have dealt with the subject in the most detailed way to date, by applying EROI estimates and associated decline functions to oil liquids at global scale as a starting point to discuss the feasibility of a Renewable Transition (RT). Yet, four points seem particularly critical in their study: (i) the authors make use of more than conservative and optimistic IEA projections that are reasonably questionable at best (Jakobsson et al., 2009; Wachtmeister, Henke and Höök, 2018); (ii) the projections date from 2014, when the Shale Revolution was only beginning, thus lowering the forecast's reliability; (iii) EROI estimates are disputable: some quantities are badly or arbitrarily chosen, the system boundaries are not specified; (iv) the sensitivity of the results against EROI scenarios is not assessed. Coeytaux (2019) explored this topic as a blog post and estimated the net-energy peak to occur 2 years in advance. Lamorlette (2020) proposed a prey-predatory model of oil production incorporating extreme parameters in line with Hill (2015) and "most pessimistic calculation in term of remaining liquid fuel)" which, in all likeliness, can be called unrealistic.

Several studies of EROI and net-energy yield for oil have been conducted on a national scale. Cleveland et al. (1984) were the first to estimate the U.S. net-energy yield from oil production. Cleveland (2005) extended this work by discussing the overall pattern of oil production and attached EROI from 1954 to 1997. Gately (2007) modeled the EROI and net-energy output of offshore oil in the gulf of Mexico. Brandt (2011) explored California net oil production from 1955 to 2005. Guilford et al. (2011) assessed the long term EROI for U.S. oil and gas including discovery and production. Safronov and Sokolov (2014) studied crude and light oil products in Russia. Subsequently, the focus of studies on oil EROI has been oriented towards China, as energy security concerns have escalated. Hu et al. (2011) began by analyzing the EROI of the Daqing oil field. Hu et al. (2013) used a multi-cyclic generalized model and a linear trend extrapolation method to predict the EROI of conventional fossil fuels. Kong et al. (2016) studied the standard EROI of oil and gas from 1996 to 2015. Wang et al. (2017a) reviewed the physical fossil fuels supply and associated EROI. Kong, Dong and Jiang (2018a) analyzed EROI for oil and gas exploration and light oil products. Kong, Dong and Jiang (2018b) calculated the net-energy impact of substituting imported oil with coal-to-liquid from a life-cycle perspective. Feng, Feng and Wang (2018) approached point-of-use EROI of fossil fuels using a dynamic function for projections and subsequently determined the future net-energy yield from 1996 to 2030. Feng et al. (2018) followed by simulating economic Gross Domestic Product (GDP) trends in China using net-energy production function. Cheng et al. (2018) calculated EROI time series of onshore and offshore domestic oil and gas. In Iran, Salehi, Khajehpour and Saboohi (2020) studied the evolution of oil and gas EROI.

Other notable works exist in the domain but attach more importance to how EROIs affect the global energy transition. García-Olivares et al. (2012) proposed a global renewable energy mix under two limiting factors: materials availability and EROI. Fizaine and Court (2015) investigated how energy requirement associated with metal extraction could impact the energy-return-on-investment (EROI) of different renewable and nuclear technologies. Based on Csala (2016), Sgouridis, Csala and Bardi (2016) modeled feasible transition pathways to achieve different net-energy levels. King and van den Bergh (2018) addressed the implications of net-energy-return-on-investment for a low-carbon energy transition that limits potential climate change to 2°C. Vidal, Le Boulzec and François (2018) described the material and energy costs associated with three different scenarios of a low-carbon energy transition. Rye and Jackson (2018) reviewed EROI system dynamics models. Manjong (2018) determined net-energy transition for Ghana, employing EROI dynamical evolution as a function of technological progression and resource quality. Brockway et al. (2019) estimated the global primary and final stage EROI ratios of fossil fuels, which could serve as the basis of a net-energy analysis, on a limited time-frame (1995–2011) but with an acclaimed rigor (Carbajales-Dale, 2019). White and Kramer (2019) explored possible forward projections of EROI in a non-scarce-energy future. Diesendorf and Wiedmann (2020) discussed the EROI aspects of a large scale transition to renewable sources for electricity supply, considering storage. Based on the WoLim model (Capellán-Pérez et al., 2014), Capellán-Pérez, de Castro and González (2019) assessed the net-energy and material investments necessary for a transition to renewable energies. They pursued by developing the integrated assessment model MEDEAS, which combines global biophysical and socioeconomic constraints relying on dynamic EROIs (Capellán-Pérez et al., 2020; Solé et al., 2020). Finally, Jackson and Jackson (2021) modeled the economic and financial impacts of declining energy return on investment in the energy transition. In addition to this literature, various works on net-energy ratios of specific energies appeared (Rana et al., 2020).

In summary and although being called out for more than a decade, researchers have to date and to the best of the authors' knowledge not explored in sufficient detail the impact of declining EROIs on the net-energy production of oil liquids on a global scale and in a long-term perspective. This study attempts to explore this question and fill the literature gap that exists today. To do so, the following three stages methodology is carried out.

First of all, a model presenting extended past and future production of oil liquids is chosen on the basis of a number of inclusion criteria. Secondly, conversion factors are applied to oil production volumes to quantify the gross energy of all liquids. Thirdly, EROIs scenarios are constructed relying on literature-based EROI estimates and decline functions for each type of oil. Net-energy curves can finally be computed and the sensitivity of the results to the developed EROI scenarios can be assessed.

3.1. Oil production models selection

Identified oil supply models have been evaluated according to eight criteria:

1. Language: either French or English;
2. Scale: global, i.e. covering the entire world;
3. Age: published after 2015 given the Shale Revolution importance;
4. Scope: all oil liquids are included to cope with a systemic perspective;
5. Granularity: production is subdivided per oil liquid;
6. Time coverage: the model provides with past and future oil production (at least 2050 and beyond);
7. Reliabilty: as experienced during the first two phases of the peak oil debate, models have sometimes proved to be based on invalid hypotheses, to involve methodological flaws and/or politically driven assumptions, from all sides (Jakobsson et al., 2009; Aleklett et al., 2010; McGlade, 2014; Laherrère et al., 2016a,b, 2017; Wachtmeister, Henke and Höök, 2018). Different options to compare a model reliability exist (Brandt, 2010; Sorrell et al., 2010a; Foucher, 2013; Peebles, 2017) but the one chosen here is to solely consider models from oil intelligence companies as they have access to sensible private data. This choice is also supported as they use field-scale bottom-up[16] models that combine both physical and economic aspects of oil production, seen as "the most promising avenue" for oil supply models (Brandt, 2010);
8. Access: data is accessible at zero or relatively low cost;

Models fulfilling the first three criteria are presented in Table 1. The chosen model is from GlobalShift (although not free, the access cost is rather modest), and presents for each oil-producing country past and projected oil production from 1950 to 2050, as well as estimates of reserves and drilled wells. Projections are available at regional, geopolitical and global scales. GlobalShift distinguishes onshore fossil oils (field oils, Natural Gas Liquids or NGLs, Shale/Tight Oils or STOs, extra-heavy oils i.e. from oil sands), onshore manufactured oils (mined shale oils, Gas-To-Liquids or GTLs, Coal-To-Liquids or CTLs, Biomass-To-Liquids or BTLs or biofuels, refinery gains) and offshore oils (0-500m, 500-1000m, 1000-2000m and 2000+ meters). Forecasts are evidence-based, validated using geological, engineering, investment and other (environmental, political, economic and social) criteria. For a recent description of GlobalShift Ltd.'s all-liquids forecast model, see Smith (2015) or the GlobalShift website.

Authors	Crit4	Crit5	Crit6	Crit7	Crit8	Score
GlobalShift	AL	✓	1950-2050	✓	✓	8
Rystad Energy	AL	✓	1900-2100	✓	×	7
IHS Markit	AO	✓	1850-2100	✓	×	6
Laherrère	AL	×	1900-2150	×	✓	6
Mohr et al.	AO	✓	1850-2300	×	✓	6
Dittmar	AL	✓	2020-2050	×	✓	5
DNV GL	AO	×	1980-2050	✓	×	5
EIA	AO	×	1973-2019	×	✓	5
ExxonMobil	AL	✓	2000-2040	×	×	5
Hosseini and Shakouri	AO	×	2013-2025	×	✓	5
IEA	AL	×	1971-2040	×	×	5
McGlade	AO	✓	2005-2035	×	✓	5
Norouzi, Fani and Ziarani	AO	×	1977-2040	×	✓	5
BP	AL	×	2000-2050	×	×	4
Equinor	AL	×	1990-2050	×	×	4
OPEC	AL	✓	2019-2045	×	×	4
Total	AL	×	2000-2050	×	×	4
Shell	AO	×	2000-2100	×	×	3
WEC	AO	×	2015-2060	×	×	3

Table 1
Models identified respecting the first three inclusion criteria, sorted in descending order by score (i.e. the total number of criteria met). AO refers to All Oils (conventional oil plus NGLs, EOR, extra-heavy oil, light-tight oil and mined shale oil) and AL refers to All oil Liquids ('all-oil' plus all other liquids such as gas-to-liquids, coal-to-liquids, biofuels, etc.). The access criteria score relies on private communications with the authors, when applicable.

3.2. Energy conversion factors

Once the oil production is constructed, it is essential to convert from a daily volumetric unit (production projections are usually expressed in thousands or millions of barrels per day) to a daily energy unit in order to quantify the energy production from all oil liquids. The process is twofold. First, the share of oil liquids destined to meet other needs than energy production (chemicals, plastics, anti-freeze products, detergents, etc.) is removed. This share is estimated to be 40% for NGLs (Solé et al., 2018) and 8% for all other liquids except biofuels, in accordance with GlobalShift estimates. Secondly, energy conversion factors are applied considering the different energy content of oil liquids. We make the conservative assumption that the share and the factors will remain constant over time. GlobalShift estimates of these energy conversion factors take into account the methodological choices adopted to define the various categories of oil liquids. These estimates lead to 4.06 GJ/bbl for NGLs and 5.9 GJ/bbl for all other liquids. These are of course rough factors only and the absolute figures will theoretically differ

[16] Models can be categorized in three types: 'field-aggregate', 'bottom-up by field' and others (system dynamics, hybrid, etc.) (Brandt, 2010).

by regions according to the API gravity[17] of the local oils. Yet, they remain a solid basis as the gravity of each national oil is unknown or only partially known.

3.3. EROIs scenarios

For this analysis, we employ the standard EROI (noted EROI_{stnd}) which accounts for the energy used in the extraction process, measuring the energy out at the well-head over the energy spent in the process (Hall, Lambert and Balogh, 2014). The desired energy level includes direct and indirect energy and material inputs . This choice is motivated by the will to reduce the boundary statistical noise (the more steps taken, the more uncertain is the estimated EROI) and the consideration of an in-between energy costs level (Murphy et al., 2011), as presented in Table 2.

Energy Inputs	Extraction	Processing	End-use
Direct energy and material	$\text{EROI}_{1,d}$	$\text{EROI}_{2,d}$	$\text{EROI}_{3,d}$
Indirect energy and material	EROI_{stnd}	$\text{EROI}_{2,i}$	$\text{EROI}_{3,i}$
Indirect labor consumption	$\text{EROI}_{1,lab}$	$\text{EROI}_{2,lab}$	$\text{EROI}_{3,lab}$
Auxiliary services consumption	$\text{EROI}_{1,aux}$	$\text{EROI}_{2,aux}$	$\text{EROI}_{3,aux}$
Environment	$\text{EROI}_{1,env}$	$\text{EROI}_{2,env}$	$\text{EROI}_{3,env}$

Table 2
Two-dimensional EROI nomenclature: boundaries for energy inputs and outputs. Source: Murphy et al. (2011).

To account for the uncertainty in EROI values and the evolution over time as well as assess the robustness of our analysis, we used a modeling approach that combines (i) a literature-based desk-research of an EROI estimate (low, medium or high) (ii) a decline function (7 different functions are considered) starting at a (iii) decline year (three decline year hypotheses are considered). The resulting panel of 39 scenarios is presented in Table 3 and implemented to estimate a set of key outputs: the year of the peak, the magnitude of the peak (in petajoule per day, PJ/d), the yearly net-energy increase from 2015-2019 to the peak (in %/yr), the yearly net-energy decrease from the peak to 2050 (in %/yr), the ratio of the decrease/increase rates and the weighted average EROI.

EROI estimates	Decline year y_D	Decline function	Scenario
	Constant scenario	DF1	H1
		DF2	H2
		DF3	H3
	2015	DF4	H4
		DF5	H5
		DF6	H6
High		DF7	H7
		DF2	H8
		DF3	H9
	$y_{prod=0.03}$	DF4	H10
		DF5	H11
		DF6	H12
		DF7	H13
	Constant scenario	DF1	M1
		DF2	M2
		DF3	M3
	2015	DF4	M4
		DF5	M5
		DF6	M6
Medium		DF7	M7
		DF2	M8
		DF3	M9
	$y_{prod=0.03}$	DF4	M10
		DF5	M11
		DF6	M12
		DF7	M13
	Constant scenario	DF1	L1
		DF2	L2
		DF3	L3
	2015	DF4	L4
		DF5	L5
		DF6	L6
Low		DF7	L7
		DF2	L8
		DF3	L9
	$y_{prod=0.03}$	DF4	L10
		DF5	L11
		DF6	L12
		DF7	L13

Table 3
Summary of all 39 scenarios considered for the scenarios-based sensitivity analysis.

3.3.1. EROIs estimates

A literature review selection on standard EROI is carried out on the basis of several criteria such as the publication date (less than 5 years preferred, less than 10 years if nothing else) or the respect of the right energy inputs and energy outputs. This allows the attribution of a low, medium and high estimate for each oil liquid. If the desired boundary or energy level is not found in the current literature, the closest estimate is searched for. For manufactured oil (biofuels, CTL, GTL), it would not make sense to exclude the processing stage that gives oil liquids and as such, it is included. The results and sources are presented in Table 4 and are followed by a presentation of the hypotheses per oil liquid.

Onshore field oil and shallow offshore (0-500m) yearly estimates have been obtained from a modified version of the base prospective model of Court and Fizaine (2017) (noted $\text{EROI}_{\widetilde{CF}}$, see appendix for more information). No decline function is thus associated to these liquids. The Ultimately Recoverable Resources (URR) for conventional of McGlade and Ekins (2015) and Miller and Sorrell (2014) are used to compute $\text{EROI}_{\widetilde{CF,1}}$ and $\text{EROI}_{\widetilde{CF,3}}$, corresponding to the low and high estimates, respectively. The URR used for the

[17] Oil API specific gravity is the inverse ratio to normal specific gravity (SG). It measures how heavy or light oil is compared to water: if it is greater than 10, oil floats on water and the oil is called light; if it is less than 10, it sinks and the oil is called heavy. This property indicates the proportion of small and large molecules, which relate to the expected Higher Heating Value (HHV) of the petroleum product (Demirbas and Al-Ghamdi, 2015; EIA, 2019), and the ability of the oil to be refined (in fact the quantity of processes needed to refine it to given specifications).

Oil liquid	Low	Medium	High	Source	EROI
Field oil	$\text{EROI}_{\widehat{CF,1}}$	$\text{EROI}_{\widehat{CF,2}}$	$\text{EROI}_{\widehat{CF,3}}$	Miller and Sorrell (2014); Court and Fizaine (2017)	$\text{EROI}_{1,\text{lab}}$
Onshore NGL	5	6.35	7.7	Campbell (2015a); Solé et al. (2018)	$\text{EROI}_{2,\text{d}}$
Shale tight oil	24.3	30.6	35.7	Brandt, Yeskoo and Vafi (2015)	$\text{EROI}_{2,\text{i}}$
Tar sands	3.48	4.96	6.44	Wang et al. (2017b)	$\text{EROI}_{\text{stnd}}$
Mined shale oil	6.37	10.75	15.12	Cleveland and O'Connor (2011); Aarna and Lauringson (2011)	$\text{EROI}_{\text{stnd}}$
Biofuels	2.32	3.12	3.92	Prananta and Kubiszewski (2021)	$\text{EROI}_{\text{stnd}}$
CTL	1.1	1.4	1.8	Kong, Dong and Jiang (2018b)	$\text{EROI}_{2,\text{d}}$
GTL	1.1	1.4	1.8	Kong, Dong and Jiang (2018b)	$\text{EROI}_{2,\text{d}}$
Offshore 0/500m	$\text{EROI}_{\widehat{CF,1}}$	$\text{EROI}_{\widehat{CF,2}}$	$\text{EROI}_{\widehat{CF,3}}$	Miller and Sorrell (2014); Court and Fizaine (2017)	$\text{EROI}_{1,\text{lab}}$
Offshore 500/1000m	23.5	29.3	35.2	Jones (2013)	$\text{EROI}_{\text{stnd}}$
Offshore 1000/2000m	11.7	14.7	17.6	Jones (2013)	$\text{EROI}_{\text{stnd}}$
Offshore 2000m+	7.0	8.8	10.6	Jones (2013)	$\text{EROI}_{\text{stnd}}$
Offshore NGL	5	6.35	7.7	Campbell (2015a); Solé et al. (2018)	$\text{EROI}_{2,\text{d}}$

Table 4
EROI estimates (X:1) for each oil liquid. $\text{EROI}_{\widehat{CF}}$ refers to the yearly estimate of the modified base prospective estimates of Court and Fizaine (2017). The EROI nomenclature follows Murphy et al. (2011).

medium hypothesis is the average of the two previous ones and leads to the computation of $\text{EROI}_{\widehat{CF,2}}$.

Onshore and offshore NGL are assumed equivalent. As no paper respecting the previously established screening rules has been found in the literature, the low estimate has been taken from Campbell (2015a), the high from Solé et al. (2018) and the medium is the average of the two.

Shale tight oil estimates derive from Brandt, Yeskoo and Vafi (2015) who evaluate standard net-energy-yields at the Bakken tight oil formation, but including processing (papers respecting the previously established screening rules have not been found in the literature). The low and high estimates are the interquartile range for the base case and the medium estimate is the mean value.

Tar sands estimates are obtained from Wang et al. (2017b) who assessed the resource EROI in Canada (the largest tar sands producing country in the world) from 2009 to 2015. We assume the overall contribution of tar sands to be made at 60% by in-situ techniques (EROI of 3.2-5.4) and at 40% by mining (EROI of 3.9-8) based on CER (2017). The medium estimate is an average of extreme values, weighted by contribution.

Mined shale oil estimates are taken from a review from Cleveland and O'Connor (2011) (low estimate) and a company estimation (Aarna and Lauringson, 2011) for the high estimate. The medium estimate is the average of both.

Biofuels estimates are obtained from Prananta and Kubiszewski (2021), who carried out a meta-analysis of biofuel Energy Return on Investment covering 44 studies across 13 countries. This choice was made as an important controversy exists in the EROI of biofuels (Hall, Dale and Pimentel, 2011). The low and high estimates respectively correspond to the values of the first and the second generation of biofuels. The medium estimate is the average of both.

GTL estimates are approached by the values of Kong, Dong and Jiang (2018b). The low, medium and high estimates represent the low, average and high values of the EROI without internal energy inputs or environmental inputs. Without this restriction, the EROI is lower than 1.

GTL estimate is used for GTL as no paper respecting the previously established screening rules has been found in the literature for gas-to-liquids oil.

Offshore oils estimates are computed using Jones (2013) equation: $\text{EROI}(h) = 5.5 \times 10^5 / (25 \times h)$ with h being equal to 750m, 1500m and 2500m for the three categories in ascending depth order. Low and high estimates are respectively a decrease/increase of 20% of the computed value, arbitrarily chosen as such to cover a wide enough range and evaluate the related impacts on the final results.

3.3.2. EROIs decline functions

EROI is theorized to depend on time as the energy production evolves due to physical depletion and technological improvement factors (Dale, 2011; Court and Fizaine, 2017). The functional dependence of EROI on time for non-renewable energy sources is assumed to start at some high level, grow rapidly to a maximum and gradually decline to reach an asymptotic limit of one. That said, those mathematical formulation of the time dependence applies to the entire exploitation history of a resource. They are thus considered inadequate for the GlobalShift data, which covers a limited portion of the resource exploitation history (1950 - 2050) and includes different resources (for instance, EROI of CTL and GTL respectively depend on the resource exploitation ratio of coal and gas).

On the basis of Dale (2011), Heun and de Wit (2012), Court and Fizaine (2017) and Solé et al. (2018), we hence define seven decline functions: the first is constant (i.e., no decline, a conservative estimate), and the remaining six start declining at the decline year. They apply for each liquid except for onshore field oil and offshore shallow oil that have yearly values. Following the modification introduced by Court and Fizaine (2017), it is assumed that EROIs cannot reach a value of less than 1 as such a value at the wellhead would imply pure energy loss. This last assumption is

Decline function	Definition	Mathematical formulation
DF1	Constant	$\text{EROI}_j(y) = \text{EROI}_j(y_0)$
DF2	Constant and linear decline$_I$	$\text{EROI}_j(y) = \begin{cases} \text{EROI}_j(y_0), & \text{if } y \leqslant y_D \\ \text{EROI}_j(y_0) - \delta_I \times (y - y_D), & \text{otherwise} \end{cases}$
DF3	Constant and linear decline$_{II}$	$\text{EROI}_j(y) = \begin{cases} \text{EROI}_j(y_0), & \text{if } y \leqslant y_D \\ \text{EROI}_j(y_0) - \delta_{II} \times (y - y_D), & \text{otherwise} \end{cases}$
DF4	Constant and geometric decline$_I$	$\text{EROI}_j(y) = \begin{cases} \text{EROI}_j(y_0), & \text{if } y \leqslant y_D \\ \gamma_I \times \text{EROI}_j(y-1), & \text{otherwise} \end{cases}$
DF4	Constant and geometric decline$_{II}$	$\text{EROI}_j(y) = \begin{cases} \text{EROI}_j(y_0), & \text{if } y \leqslant y_D \\ \gamma_{II} \times \text{EROI}_j(y-1), & \text{otherwise} \end{cases}$
DF6	Constant and exponential decline$_I$	$\text{EROI}_j(y) = \begin{cases} \text{EROI}_j(y_0), & \text{if } y \leqslant y_D \\ \text{EROI}_j(y_0) - e^{\frac{y-y_D}{\tau_I}}, & \text{otherwise} \end{cases}$
DF7	Constant and exponential decline$_{II}$	$\text{EROI}_j(y) = \begin{cases} \text{EROI}_j(y_0), & \text{if } y \leqslant y_D \\ \text{EROI}_j(y_0) - e^{\frac{y-y_D}{\tau_{II}}}, & \text{otherwise} \end{cases}$

Table 5
Summary of EROI decline functions (DF), $\text{EROI}_j(y_0)$ being the initial EROI value at the year 1950 for the oil liquid j. They apply as long as $\text{EROI}_j(y)$ is greater or equal to 1, which is the minimum value EROI can hypothetically reach. The models' constants derive from the authors and the scenarios of Heun and de Wit (2012) with δ_I, δ_{II}, γ_I, γ_{II}, τ_I and τ_{II} being respectively equal to 0.25 year^{-1}, 0.125 year^{-1}, 0.95, 0.975, 43 years and 116 years.

important but is supported by the use of a modified version of Court and Fizaine (2017) model for onshore field oil and offshore shallow oil (see Appendix). The decline functions and their mathematical formulation are presented in Table 5.

3.3.3. *EROIs decline years*

For each of the non-constant decline functions, two decline-years are used: 2015 (i.e., a nearly common year of publication for all selected papers, the idea being that these papers quote the current EROI at the time of publication) and the year when the production of the oil liquid reached or will reach 3% of the total gross energy production (in energy content and not volumes). This decline-year noted $y_{j,prod=0.03}$ is chosen as such to represent a domino decline year for each oil linked to the resources production history in the vein of Court and Fizaine (2017). It is to 2050 for the offshore NGL, offshore 500/1000m, CTL and mined shale oil. The corresponding decline years are 1994, 2007, 2013, 2014, 2026, 2028 and 2042 for onshore NGL, offshore 1000/2000m, tar sands, shale tight oil, offshore 2000m+, biofuels and GTL, respectively.

4. Results

4.1. Net vs. gross energy from oil liquids

According to GlobalShift (2020), the oil liquids production for energy purposes should peak in 2034 with a magnitude of 551 PJ/d. Removing the energy necessary for the liquids extraction and production (including direct plus indirect energy and material costs), we find that the net-energy reaches a peak in 2024 of 415 PJ/d, with respective standard deviations over all scenarios being equal to 6.6 yr and 26.7 PJ/yr. This first result should not be interpreted as the announcement of a coming peak, but as an indication that by 2024, the production of oil liquids will require an amount of energy equal to 25% of its energy production. Yearly increase has been diminished by 69% (from 1.26%/yr to 0.39%/yr) while the yearly decrease has been lowered by 28%. Most notably, the ratio of the decrease rate over the increase has experienced an increase of 445%: from 1.28 to 6.97. If the year of the peak and the magnitude matter, this ratio seems to be the most crucial factor as it implies important and accelerated energy needs from the oil liquids sector. In particular, the energy required for energy production will reach a staggering proportion of 50% by 2050. The contribution in terms of gross energy of the oil liquids is led by onshore field oil (63%) followed by offshore shallow oil (20%), while the rest does not exceed 3% per oil liquid. For instance, shale tight oil and oil sands input are limited to small fractions of 3% and 2%. The contribution in terms of net-energy is close, with a weighted average total difference of 0.1%. However, unconventional oils begin to grow in proportion starting from the shale revolution and the yearly contribution undergoes important changes: onshore field oil and shallow offshore are expected to equal about 51% of the gross energy production in 2050. Figure 1 presents the average oil liquids net-energy production from 1950 to 2050.

The weighted average EROI (based on the gross energy contribution) experiences a steady decline from its initial maximum value of 44.4 to its apparent final plateau of 6.7. This reduction is predominantly led by the decrease in EROI of onshore field oil and shallow offshore, until both curves drift apart, from 2013 onwards, as Figure 2 shows. Let us also note that each EROIs tends to decrease, but at

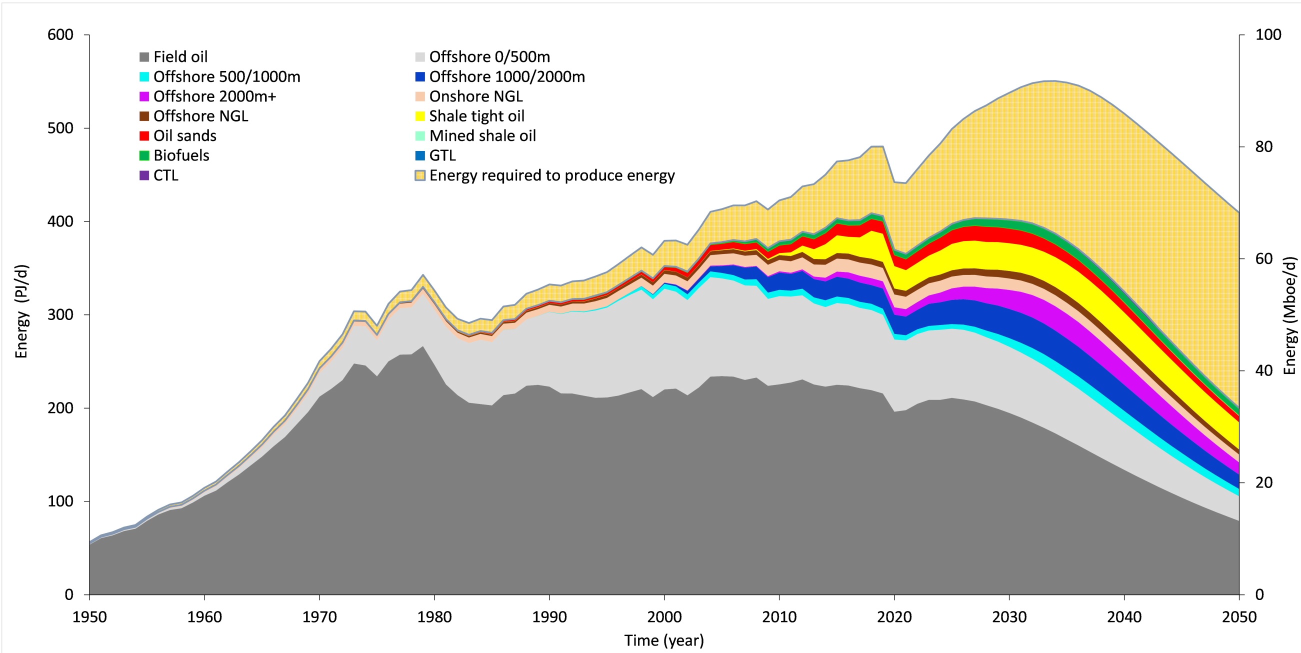

Figure 1: Average oil liquids net-energy production from 1950 to 2050, compared to the gross energy.

different rates, which is explained by the different decline-years (see for instance the difference between shale tight oil and offshore 500/1000m).

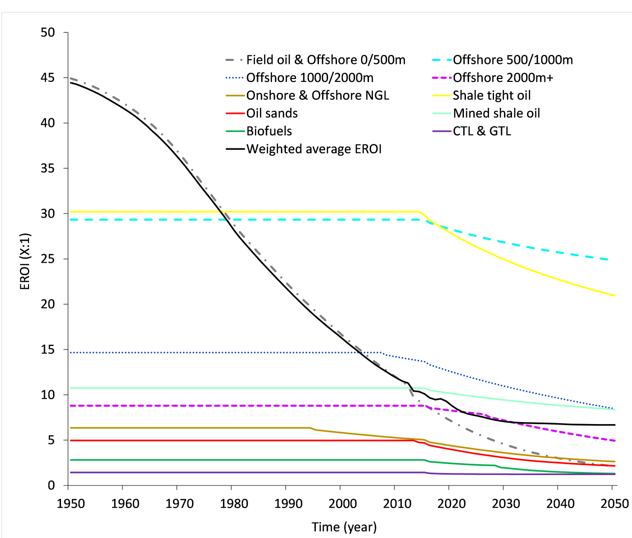

Figure 2: Evolution of each liquid standard EROI and the weighted average EROI, from 1950 to 2050.

The energy required for the production of oil liquids grows from 1.5 PJ/d in 1950 to 210 PJ/d in 2050, with an exponential increase until reaching an apparent plateau. apparent plateau. This represents 15.5% today of the gross energy production, and is projected to reach 50% by 2050, as illustrated in Figure 3. In other terms, an amount equivalent to half of the energy production of oil liquids will be necessary in 2050 in order to keep producing. Nevertheless, the precise breakdown by energy sources remains to be treated in future research.

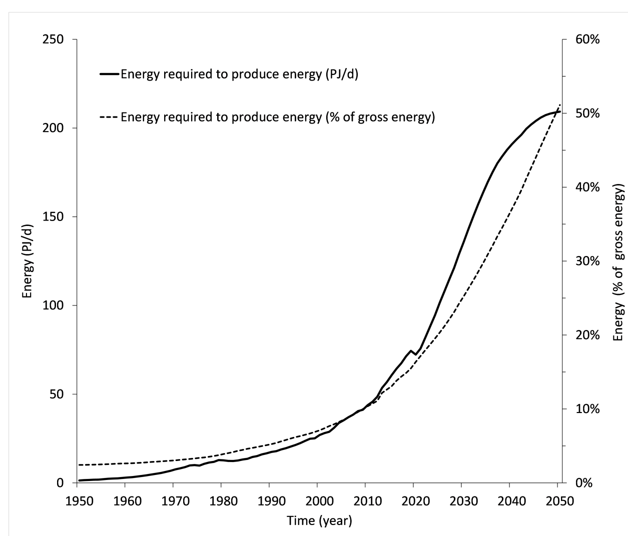

Figure 3: Evolution of energy required to produce oil liquids, from 1950 to 2050.

4.2. Scenarios-based sensitivity analysis

4.2.1. EROIs estimates

As one could expect, reduced EROI estimates induce a lower peak year: the high, medium and low hypothesis respectively correspond to a peak year of 2030, 2024 and 2017, respectively. In a similar fashion, the net-energy peak magnitude reaches 444, 417 and 383 PJ/d, while the 1950 - 2050 average EROI goes from 24.4, 22.7 and 20.5. Diving the difference between high and low outputs by the medium output, we find that the peak magnitude and average EROI have similar uncertainties (15% and 17% respectively). Let us note that these results are also in line with the dominance of onshore field and offshore shallow oil in the overall gross energy production (83% of the total contribution). To assess future projection uncertainties, one should focus on these two sources of oil liquids first, short of a major technological revolution making another source much more accessible than it presently is.

4.2.2. EROIs decline years

The decline years present more similar features than the EROI estimates. The constant scenarios (H1, M1 and L1 in Table 3) reach on average a peak of 427 PJ/d in 2027 with a decrease/increase ratio of 2.8 and an average EROI of 23.4. Other decline-years hypotheses lead to a peak of 414 PJ/d in 2023, with a decrease/increase ratio of 3 and an average EROI of 22.4. The difference between the first decline-year hypothesis (2015) and $y_{j,prod=0.03}$ is rather negligible in terms of peak year, magnitude or average EROI, but not for the ratio. Two lessons can be drawn from this. Firstly, decline-years have lower impact on the assessed outputs than the EROI estimates. Secondly, taking in consideration decline functions for all liquids (except field oil and shallow offshore oil that already have yearly values) generates an earlier, lower and steeper peak, but with rather close outputs. Still, these results highlight the significance of incorporating decline functions to net-energy forecasts and not solely sticking to static estimates of EROIs.

4.2.3. EROIs decline functions

In a logical way, outputs that induce a steeper EROI decline have resulted in higher reductions in net-energy peak, and higher decrease/increase ratios. We find that the exponential and geometric decline functions are the most optimistic whereas the linear function hypothesis leads to small average EROI values. Putting aside the linear function, the EROI plateau previously identified reaches 12. This is an important finding as our data could be used in future energy transition models integrating a net-energy perspective.

4.3. Robustness of the results

In order to analyze the robustness of the results, we constructed a 3-level robustness scale. "0" indicates that the evaluation of the net-energy does not give a significant qualitative and quantitative variation compared to the gross energy (when the difference between gross and net-energy output values is less than half of the average standard deviation of net-energy), "+" indicates a qualitative significance (when the difference is of the order of the standard deviation) and "++" a qualitative and quantitative significance (roughly speaking, when the difference is more than twice the standard deviation). From this scale, it appears that net-energy is clearly robust for the peak magnitude and the pre-peak net-energy increase rate, both on the qualitative and quantitative fronts. It is also qualitatively significant for the peak year, the post-peak decrease rate and the decrease/increase ratio. The results testify that, in all likelihood, relative trends are independent of our choice of gross energy data. Table 6 gives the robustness evaluation outputs.

Output assessed	Gross en.	Net en.	$\lvert\frac{x_{gross}-x_{net,avg}}{\sigma_{net}}\rvert$	Scale
Peak year	2034	2023.6	1.6	+
Peak magnitude	551	415	5.1	++
Pre-peak increase	1.26	0.39	5.7	++
Post-peak decrease	1.60	2.04	1.4	+
Decrease/increase ratio	1.28	6.97	1.7	+

Table 6
Comparison between gross and net-energy outputs to estimate the robustness of the results.

Moreover, and even though the expected peak date and production may differ somewhat from one set of data to another, the EROI trend models as quantified in this work do not (as our quantification of these trends are independent of the type of future production projection used). Furthermore, when comparing the volumetric projection of the three all liquids models with the highest model score (GlobalShift, Rystad Energy, Laherrère), one can note the overall similarity in terms of peak year and magnitude trends (Figure 4). This assertion is furthermore reinforced when integrating projections discussed in the introduction, although which yearly values were not made available to us.

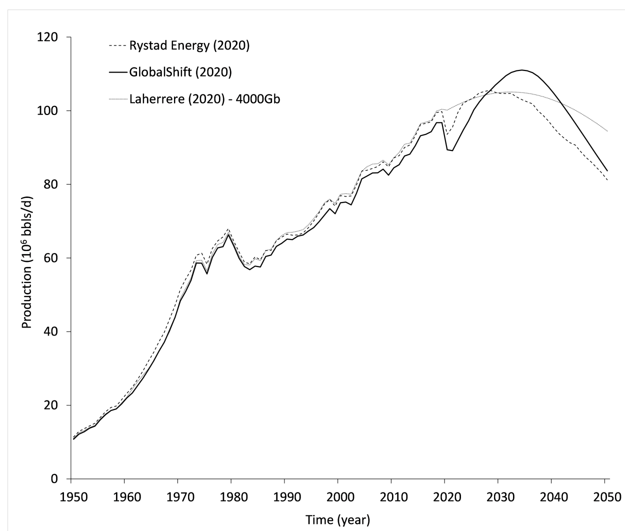

Figure 4: Comparison of the three oil production models with the highest model score made available to us, see Table 1.

5. Discussion

5.1. Implications for a global and fast low-carbon energy transition

This study uses GlobalShift's all oil liquids projection and a panel of standard EROI scenarios to characterize the dynamic evolution of the primary stage net-energy along the transition from high quality conventional to low-quality unconventional resources. Several key findings appear.

Firstly, the gross energy production from oil liquids is likely to peak in the next 10 to 15 years. The overall contribution of unconventional liquids is relatively low until the mid 2010's, when their gross energy production starts to increase to reach about half of the conventional at its peak. (Figure 5). If the shale tight oil has been able to compensate for the production plateau of conventional oils since the mid 2000's, no other liquid is expected to take off and become the next backstop energy source.

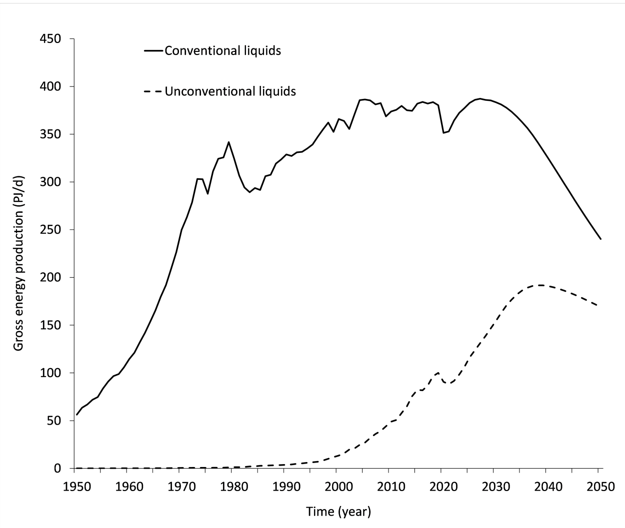

Figure 5: Gross energy production from conventional (onshore field oil, shallow offshore and NGL) and unconventional oil liquids (others).

Secondly, the energy necessary for the production of oil liquids is estimated to equal 15.5% of the oil energy production today, and is expected to grow exponentially to reach 50% in 2050. We thus foresee an important consumption of energy to produce future oil liquids, a phenomenon relating to "energy cannibalism" (Pearce, 2008). We point out that our model features are robust on the qualitative side, and for some on both on the qualitative and quantitative fronts. Moreover, the comparison of gross energy models shows that a gross peak is expected by 2035 with approximately similar shapes, even though GlobalShift demonstrates a steeper decline. In other terms, it means that the relative trends from our results are in all likelihood, independent of the choice of gross energy data. Finally, the weighted average EROI of oil liquids is expected to reach a low plateau of 6.7.

On the one hand, we clearly have too much fossil fuels stock to respect ambitious climate targets (McGlade and Ekins, 2015). On the other hand, the flow from oil liquids (which might be needed for the transition while maintaining a growing economy) may be constraining, especially from a net-energy perspective. In this context, two different energy transition scenarios may be envisaged and discussed in light of the 2°C maximum climate target of the Paris Agreement.

The first are rapid transition scenarios to low-carbon energies, which, as their deployment is only one component of fossil fuel use, appear to be marginally affected by a net-energy reduction from oil liquids. However, such scenarios bear possibly unrealistic deployment rates of low-carbon energy and derived end-use technologies (for example in terms of structural metals or minerals production increase and associated costs) and/or emission trajectories (due to the transition itself and potential rebound effects[18]). (Geo)economic realism, the delays required for large scale deployment of nuclear power plants, the self-sustainability of renewables or the technological limits that they generate in the electrical grid are other constraints. These limitations consequently question the feasibility and validity of rapid transitions scenarios (Kramer and Haigh, 2009; Smil, 2010; Solomon and Krishna, 2011; Loftus et al., 2014; Sovacool, 2016; Grubler, Wilson and Nemet, 2016; Smil, 2016; Fouquet, 2016; Napp et al., 2017; Smil, 2017; Vidal, 2018). It thus seems more reasonable to think that (or at least question whether) fast scenarios on the one hand are limited upstream by the rate of deployment, and on the other hand, the energy flow may be constrained downstream.

The second types of scenarios are slower low-carbon energy transitions, but they come up against the availability of cheap oil liquids in the 2030's. They would thus impose a decrease in oil consumption, with consequent adverse effects. For instance, a period of economic doldrums can happen as large scale and long-term decoupling seems impossible (Hickel and Kallis, 2019; Parrique et al., 2019; Haberl et al., 2020; Vadén et al., 2020a,b; Mastini, Kallis and Hickel, 2021). Such scenario could also mean an abandonment of the previous climate target and would further accentuate the "carbon crunch" effect (Figueres et al., 2017): the more we wait (*n* years to start curbing GHG emissions), the less time we have for any given carbon and climate warming target (reduction of available time by 2*n* years).

The question is: is there a window between the two types of scenarios? Does this window force choices/shocks on critical/priority areas and the role of nuclear energy in the transition? If so, of what kind? What are the links with investment inertia in the sector concerned, but also in the primary mining and secondary (renewable) sectors concerned? Do these inertias lead to price or financial instabilities? If so, according to which broad categories of scenarios? With what implications for all critical sectors? Another "crunch" appears at this level: no growth (or less than 2% of global growth) might generate a global economic shock and new questions about critical/priority sectors.

5.2. On the debate's future and the pitfall of the peak supply vs. peak demand dispute

However, we anticipate that these questions–beyond the scope of the present article–might be superseded by another side of the discussion. As the peak oil debate has been dormant over the last decade or so, focus has been directed

[18]According to Brockway et al. (2021), the rebound effect of energy efficiency is largely underestimated and might reach half of the savings made.

onto the peak supply vs. peak demand confrontation. Proponents of the second hypothesis have gradually taken over, benefiting from the deterioration of the peak oil debate and from the shale revolution. We argue that the point is not here and by restraining ourselves to this dual confrontation, we would only repeat the pitfalls of the preceding peak oil debate. Oil is a commodity like no other as it is the lifeblood of our society with intricate political interests. A contracting window exists between oil prices high enough so that extraction and development are viable, and low enough to let consumers have access to it (Murphy, 2014). From this perspective, peak oil will never be either totally peak supply nor peak demand, but a mix of both in proportions that are difficult to measure and project. Given the issues at stake, we therefore urge for a renewal of the peak oil debate in the larger context of energy transitions.

5.3. Limitations and future work

This study presents a quantitative analysis of the differences between net and gross energy production of all oil liquids. However, the methodology adopted suffers from a number of limitations that we now discuss. The first one concerns the uncertainty of GlobalShift's gross energy forecast, exacerbated today by geopolitical tensions surrounding the resumption of oil production in a COVID-recovery and climate emergency context. Globalshift's model currently assumes that demand for oil will continue on a 'business-as-usual' basis, which may not be the case if very strong climate-change restrictions–such as significant levels of carbon pricing–are implemented. Like other detailed bottom-up modellers, Globalshift recognises that if the oil price goes really quite high, then more unconventional oil can certainly come on-stream from some countries. These countries, though probably not too many, have potentially quite large recoverable resources of unconventional oils, including Canada (tar sands oil), Venezuela (heavy oil), Argentina, Russia and China ('light-tight' shale oil from fracking), and the U.S. (mined shale oil). But under most scenarios, much of this unconventional oil only comes on-stream fairly slowly after current resource-limited oil production peaks (the U.S. shale oil boom being the exception because of good resources, advanced technology, ample speculative finance, and beneficial land/resource ownership rules, as discussed). Globalshift does include such production in its forecasts, but points out that it is hard to be certain about future rates of production from new-–and possibly quite expensive in most cases–oil resources. Moreover, it is difficult to assess GlobalShift's model robustness as similar bottom-up models require a great deal of data and assumptions (Jakobsson et al., 2014). We have pointed out earlier, though, that because all gross production models share similar features (similar overall production projection shape) the results obtained here should be qualitatively correct, and in all likelihood semi-quantitatively correct in net vs gross relative difference. Still, the most robust conclusions drawn from this study (small relative shift for the peak year and substantial relative decrease for the peak production) do depend, once translated in absolute terms, on the gross production features, and most importantly, the expected peak date. Having a feel for the uncertainty of this feature would definitely help us to sharpen our conclusions. A second limitation lies in the use of the GlobalShift model. Even though it is a field scale model, the restricted granularity level made available to users has precluded us from implementing a more precise type of depletion analysis (Höök et al., 2009). On the other hand, other field scale models are usually sold at a very high price by oil intelligence companies that may have restricting publishing policies, which is not the case of GlobalShift. Unlike climate change related information, the public release of oil data conflicts with forceful private interests and internal security matters. Thus, building reliable projections is a complex and intricate task, as obtaining trustworthy data on oil availability is difficult.

Thirdly, a limitation arises from EROI assumptions on estimates, decline functions and decline years. Indeed, selecting EROI estimates on the basis of drastic inclusion criteria has proven to be difficult to respect and altogether make estimates questionable (Raugei, 2019). The use of decline functions and decline years although based on the literature may also have induced uncertainty in the results, as the dynamic evolution of EROI is still an emerging topic. It could be pointed out that an incline function could have been taken in consideration for unconventional oil. However, we believe that incline functions for unconventional oils at a global scale appear very unlikely for extraction[19] and not significant as conventional oil represents more than 80% of the overall gross energy production. These two categories have better known EROIs than the others and necessarily limit quite substantially the usefulness of further sensitivity analysis and enhance the reliability of the results obtained. Nonetheless, we implemented constant scenarios without decline functions and scenarios with late decline years to balance for a hypothetical growth. More largely, uncertainties surrounding EROI are partly reduced by the set of scenarios and the sensitivity analysis. Fourthly, the existing literature on EROI has prevented the comparison between standard and societal EROI, a more meaningful viewpoint (Brockway et al., 2019). However, restraining ourselves to standard EROI has made the comparison between each EROI more reliable (the basis of comparison being clearer and closer to the physical extraction and other processes, and therefore less open to interpretation). Finally, the major limitation of this study resides in its prospective nature: the scenarios presented will in all likeliness not depict reality. And it should be kept in mind that this is not the objective of this article, as we are more interested in estimating the impact of net-energy relative to gross energy rather than guessing the timing and magnitude of a peak.

The assessment of more precise policy reactions to peak oil would constitute a useful improvement; this aspect is not sufficiently developed in the GlobalShift model –a deliberate

[19] See for example the long-term evolution of mine-mouth net-energy return and net external energy return of oil sands (Brandt, Englander and Bharadwaj, 2013).

modelling choic[20]. This can be done by (i) predicting oil producing countries' reaction to peak oil (ii) developing policy reaction scenarios from oil demanding countries (Correljé and van der Linde, 2006). This distinction is key as friendly or hostile behaviors can emerge from the peak, with producing countries adapting to consumption per geopolitical affinity or reducing oil exports under the double constraint of both a peak in oil production and an increase in domestic oil consumption[21] (Matutinović, 2009; Verbruggen and de Graaf, 2013; Bradshaw, de Graaf and Connolly, 2019).

6. Conclusions

Our society can be described as a thermodynamic system that profoundly relies on abundant cheap energy sources such as petroleum to thrive. However, the rapid growth in use of this non-renewable fossil fuel has undermined its future availability, leaving little doubt that an all-oil liquids peak will take place in the next 10 to 15 years. Given the societal dependence on oil and the difficulties in achieving a transition to low-carbon energies in time, such a peak is likely to have deep consequences that are not yet fully understood and which might handicap the transition itself.

When removing the energy necessary for these liquids' acquisition, this peak is not only sooner or reduced in terms of magnitude but also—and perhaps more importantly– carries a greater ratio between the decrease post-peak and the increase pre-peak rates. The total energy needed for the oil liquids production thus continually increase from a proportion equivalent today to 15.5% of the gross energy produced from oil liquids, to the half in 2050. We thus foresee an important consumption of energy to produce future oil liquids. If our approach is subject to various uncertainties, the gaps between net and gross energy are statistically significant to uphold that our results are qualitatively and to some extent quantitatively robust. This conclusion is further supported when most robust oil production models are compared with one another.

Our findings question the feasibility of a global and fast energy transition, not in terms of stocks of energy resources, but in terms of flows. They imply that either the global energy transition takes place quickly enough, or we risk a worsening of climate change, a historical and long-term recession due to energy deficits (at least for some regions of the globe), or a combination of several of these problems. In other terms, we are facing a three-way conundrum: an energy transition that seems more improbable every passing year, increasing environmental threats and the risk of unprecedented energy shortages and associated economic depression in less than two decades. This leaves no room for approximation and poor judgment. Given the issues at stake, we therefore urge a renewal of the peak oil debate in the larger context of energy transitions but including consideration of net-energy, wise energy consumption and avoiding focusing simply on 'peak supply' vs. 'peak demand'. We see this conclusion not simply as a cautionary note, but as a call to scientific and political responses.

[20]Globalshift acknowledges there are many possible futures, their model is an attempt at a "most likely" version under present day economic, environmental etc. expectations, to be used to develop more nuanced predictions.

[21]This theory is also known as the "export land model" and is based on the work of Jeffrey Brown (Tverberg, 2010).

CRediT authorship contribution statement

Louis Delannoy: Conceptualization, Data Curation, Formal Analysis, Methodology, Project Administration, Writing - original draft, Writing - review & editing. **Pierre-Yves Longaretti**: Formal Analysis, Funding Acquisition, Supervision, Validation, Writing - review & editing. **David J. Murphy**: Methodology, Validation, Writing - review & editing. **Emmanuel Prados**: Funding Acquisition, Supervision.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Appendix A - Modified base prospective model of Court and Fizaine (2017)

Following Dale, Krumdieck and Bodger (2011a), Court and Fizaine (2017) define the EROI of a non-renewable energy resource as:

$$\text{EROI}(\rho) = \varepsilon F(\rho) = \varepsilon G(\rho) H(\rho) \tag{4}$$

With ρ being the exploited resource ratio (historical cumulative production over the Ultimate Recoverable Resource, ratio comprised between 0 and 1) and ε a scaling factor which represents the maximum potential EROI value (never formally attained). The function $G(\rho)$ represents a technological component that increases EROI and $H(\rho)$ represents the physical component that diminishes EROI as resources are depleted. They read:

$$G(\rho) = \Psi + \frac{1-\Psi}{1+\exp(-\psi(\rho-\widetilde{\rho}))} \tag{5}$$

$$H(\rho) = \exp(-\varphi\rho) \tag{6}$$

Ψ represents the initial EROI with immature technology, ψ the rate of technological learning, $\widetilde{\rho}$ the exploitation ratio for maximum growth rate of EROI and φ the rate of degradation of the resource. From historical estimates of EROI obtained with a price-based methodology (especially suited for conventional oil only), Court and Fizaine (2017) find the best fit values of Ψ, ψ, $\widetilde{\rho}$ and φ using a minimization procedure of the sum of square root errors. However, the production ratio ρ is found using an URR that includes conventional and unconventional oils, and is therefore not relevant to our analysis of on conventional oil only. Thus, a modified version of yearly EROI estimates is computed using a similar method but with a URR of 15,000 GJ for the low estimate McGlade and Ekins (2015), 24,665 GJ for the high Miller and Sorrell (2014) and 19,833 GJ (the average of both) for the medium hypothesis. Figure 6 presents the different yearly EROI estimates for each high, medium and low URR hypotheses.

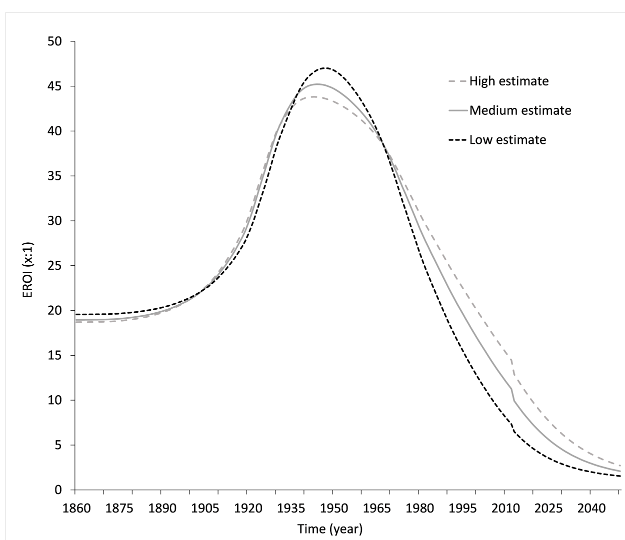

Figure 6: Yearly EROI estimates for conventional oil, from a modified Court and Fizaine model (Court and Fizaine, 2017). The drop-off towards 2012 is linked to the reconciliation of the EROI calculation with the historical and prospective rho.