Journal Name

ARTICLE TYPE

Cite this: DOI: 00.0000/xxxxxxxxxx

Emerging consensus on net energy paves the way for improved integrated assessment modeling

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Extracting, processing, and delivering energy requires energy itself, which reduces the net energy available to society and yields considerable socioeconomic implications. Yet, most mitigation pathways and transition models overlook net energy feedbacks, specifically related to the decline in the quality of fossil fuel deposits, as well as energy requirements of the energy transition. Here, we summarize our position across 8 key points that converge to form a prevailing understanding regarding EROI (Energy Return on Investment), identify areas of investigation for the Net Energy Analysis community, discuss the consequences of net energy in the context of the energy transition, and underline the issues of disregarding it. Particularly, we argue that reductions in net energy can hinder the transition if demand-side measures are not implemented and adopted to limit energy consumption. We also point out the risks posed for the energy transition in the Global South, which, while being the least responsible for climate change, may be amongst the most impacted by both the climate crisis and net energy contraction. Last, we present practical avenues to consider net energy in mitigation pathways and Integrated Assessment Models (IAMs), emphasizing the necessity of fostering collaborative efforts among our different research communities.

Broader context

The transition from fossil fuels to low-carbon energy is made difficult by several factors. One of which is the energy investments required by the transition, often examined through the lens of the EROI (Energy Return on Investment) metric. Although the concept of EROI is simple, its application has proven to be challenging due to theoretical and practical difficulties. To address this situation, we summarize our position with 8 key points, which approximate an emerging consensus around EROI, and identify key areas under investigation for the Net Energy Analysis research community. Our summary uncovers how net energy is critical for the assessment of equitable and feasible transition scenarios, and yet how it remains marginally addressed in the current use of Integrated Assessment Models. We therefore suggest avenues for improvements to make sure that energy-economy feedbacks are internally consistent in mitigation pathways.

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Introduction

On April 4 2022, IPCC Working Group III finalized its contribution to the Sixth Assessment Report. Reviewing progress and commitments for climate change mitigation, the report calls for more sustainable consumption habits and a shift away from fossil fuels towards low-carbon energy systems [1]. This transition nevertheless requires significant energy investments for the alternative low-carbon energy system, which can be examined through the lens of the Energy Return on (Energy) Invested or ERO(E)I metric [2,3]. Recent developments in the Net Energy Analysis (NEA) research community have highlighted EROI implications for socio-economic scenarios [4–8], in particular regarding the practical challenges of the low-carbon transition. Yet, in part due to a lack of formal methodology prior to the 2010s [9,10] and to a delay in the emergence of robust results, such studies have failed to influence transition scenarios. To remedy this situation, we provide an overview of the net energy approach, summarize the claimed emerging consensus around EROI, address how it relates to the low-carbon transition, and suggest ways to better integrate net energy in Integrated Assessment Models (IAMs).

The Net Energy Analysis approach

Net energy, i.e. the energy supplied to society in the form of energy carriers after subtracting the energy invested for the production and distribution of those energy carriers, is a fundamental prerequisite to allow the production and exchange of goods and services. For a given amount of net energy, a key metric of the energy system is the EROI – defined as the ratio between the total energy returned ($E_{returned}$) and the total energy invested to accomplish the conversion ($E_{invested}$) over the entire life cycle of the system under study, i.e. $EROI = E_{returned}/E_{invested}$.

As with all analyses that can be performed at the macro (economy-wide) and micro (technology-specific) scales, EROI can have slightly different interpretations [11–13]. For example, at the scale of the global economy, the EROI has a minimum of 0 based on the first law of thermodynamics. When analyzing a single technology or energy subsystem that produces a final energy carrier, the EROI ratio can be less than one to one (1:1) (e.g., in Figure 1, $E_{invested,2}$ is greater than $E_{returned,2}$). Such systems can still be locally or temporarily useful when they have compelling properties, for example delivering a specific energy carrier that is in particular demand, e.g., the industrial food system, but they cannot be a main supplier of energy for society. Although the equations involved are simple, their application entails theoretical and practical difficulties that call for a rigorous definition of the system's boundaries [14,15].

The "standard" (or primary stage) EROI accounts for the energy used in the extraction process only. It is useful for studying the energy demand of a primary energy extraction sector or technology.

The point-of-use (or final stage) EROI includes the energy used in not only extracting, but also processing and delivering an energy carrier. Therefore, for a given energy carrier, the point-of-use EROI is substantially lower than the standard EROI since additional energy inputs are considered. Focusing on the point of use is gaining in importance, as: (i) the energy requirements of processing, refining and other downstream processes for fossil fuels may be larger than that for their extraction, and (ii) most renewable energy systems directly deliver final energy carriers, i.e., typically electricity, making the analysis at the final energy stage essential to compare renewable and fossil fuel energy systems like for like*.

The dynamic EROI of the full energy system corresponds to the energy delivered by a country's (or the entire world's) energy system divided by its energy consumption at a given time, and is in that respect a Power Return on Investment (PROI) as the calculation is performed for a delimited time interval (one year usually) [12,16].

Emerging consensus on net energy

As researchers in the field of NEA, we summarize our position with the following 8 key points, which approximate an emerging consensus around EROI:

1. The standard EROI of oil is usually lower than that of gas, which is lower than that of most coal [17].

2. Conventional fossil fuels (crude oil, natural gas liquids, etc.) may have lower standard EROIs than tight gas and oil produced from fracking [18,19] but higher than other unconventional fuels (tar sands, mined shale oil, coal bed methane, etc.) [6,20,21].

3. The standard EROI of new fossil energy resources is expected to improve initially as technology develops, before decreasing due to a decline in the quality of the ex-

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* Discussion is still on-going in the research community about some subtle methodological issues on exactly how EROI at point of use should be formulated, but these do not affect the main argument being made here, i.e., that in order to be meaningful, all such comparisons should in fact be made at point of use.

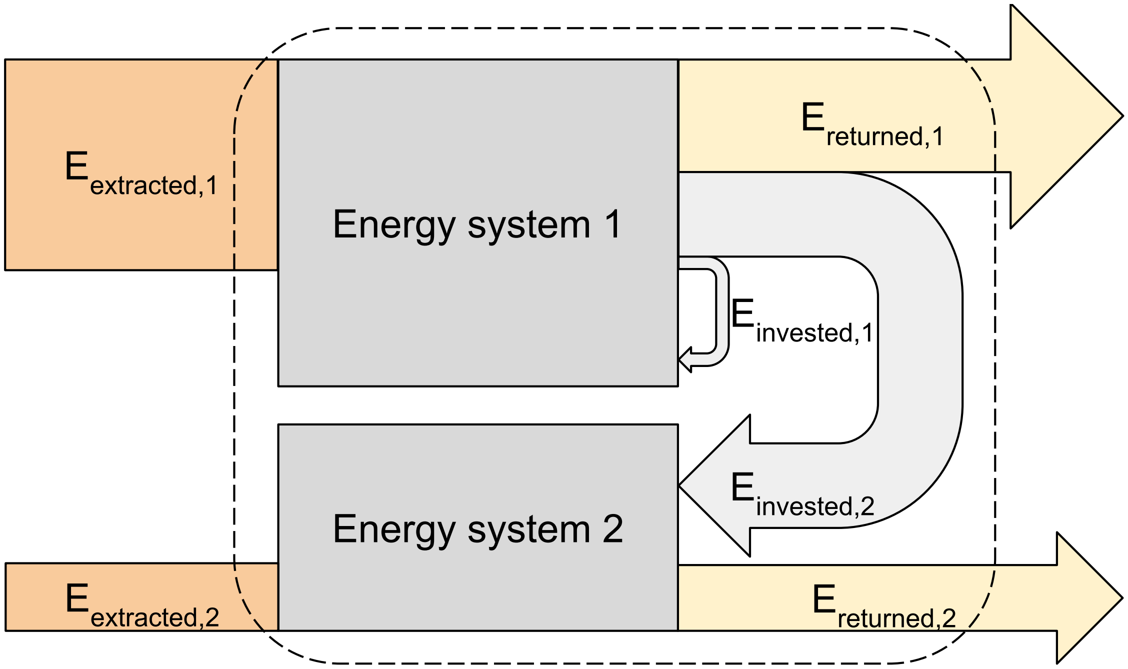

Fig. 1 Returned energy as a function of the extracted and the invested energy for two systems. EROI (global) = $(E_{returned,1} + E_{returned,2})/(E_{invested,1} + E_{invested,2})$. EROI (energy system 2) = $(E_{returned,2})/(E_{invested,2})$. Energy losses are omitted for clarity.

tracted resource[22,23]. For instance, the standard EROI of oil sands-derived crude has been increasing since the first bitumen-producing mines became operational[24]. On the contrary, many major conventional oil fields have already seen marked decreases in their standard EROI due to the requirements for enhanced recovery[25] and global resource depletion, as evidenced by the decline in the quantity of the remaining "2P" (proven and probable) reserves[26,27].

4. The aggregate EROI of fossil fuels at the point of use declines over time, albeit at a slower pace than at the point of extraction, since the largest investment (at the denominator of the EROI ratio) is not the energy required for extraction (that increases over time as resource quality decreases) but the subsequent energy required for processing and delivery (which is generally not much affected by the quality of the resource over the long-term)[28].

5. Today, the EROI of fossil-fueled electricity at point of end-use is often found to be lower than those of PV, wind and hydro electricity, even when the latter include the energy inputs for short-term (e.g., 8h) storage[†] technologies[29,30]. Average EROI values however hide strong regional variability, particularly for solar and wind technologies[31,32].

6. The EROI of nuclear and hydropower have historically been high, however, the former is constrained by slow deployment times, the latter is limited in terms of availability of suitable locations, and both face many environmental considerations.

7. The point of use EROI for thermal fuels is usually low, specifically for liquid fuels (gasoline, biodiesel, bioethanol, etc.) compared to solid (coal, woodchips, etc.) or gaseous fuels[30].

8. A rapid large-scale deployment of renewable electricity and associated infrastructure will likely temporarily reduce the dynamic EROI (i.e., PROI) of the energy system as it requires a significant up-front energy investment embodied in infrastructure[7,8,33–36].

In parallel to this emerging consensus, several areas are under investigation, such as the future EROI trends of wind and solar. On one hand, their EROI might be negatively affected by the increase in energy requirements per unit of valuable mineral extracted due to geological depletion[37], whereby the quality of mineral deposits extracted (e.g., in terms of ore grade) decreases as a function of cumulative production. On the other hand, technological improvements may favorably affect the EROI of wind and solar PV[38]. The same is true for increasing the recycling capacity of renewable energy technologies, but the delay is significant because of the time required to build up a stock of materials suitable for recycling.

Another area under scrutiny is the extension of the analysis to the useful stage of energy use, i.e. at the stage when energy is actually exchanged for energy services[39] (see Figure 2) as some energy carriers may be used for similar end-uses with very different final-to-useful efficiencies[40]. For example, electricity might fuel

† The inclusion of storage devices in the system boundary (rather than at the level of an individual power generation technology), however, is more relevant at the country, regional, or grid level, because each technology, if deployed in isolation, would require some storage capacity to successfully keep up with the pattern of electricity demand.

a car at a lower $EROI_{point-of-use}$ than gasoline, but an electric vehicle motor has a considerably higher final-to-useful efficiency in converting its fuel input into mechanical drive when compared to a traditional internal combustion engine, such that an electric vehicle can have higher EROI at the useful stage.

Of particular interest is the use of net energy analysis at the useful stage for a comprehensive understanding of the rebound effect at different geographic and time scales. More precisely, this approach can help explain why global data shows energy use continuing to increase as individual technologies become more efficient, suggesting it is difficult to disprove that, to date, increased efficiency has enabled increased energy use. Models that attempt to quantify rebound show large rebound effects (typical economy-wide estimates are over 50%) [41].

Implications for the low-carbon transition

The net energy approach provides an enhanced understanding of the role of energy in economic processes, and as such, the EROI concept is increasingly used to model the energy–economy nexus. This growing modeling effort highlights two main net energy aspects which have implications for the low-carbon transition. On the one hand, the decline in the standard EROI of oil and gas may entail a rise in emissions per unit of net energy supplied to society [42], and long-term energy price increases [43,44], leading to periods of unfavorable growth or recession, especially for slow transition scenarios. On the other hand, the–perhaps only temporary–reduction in net energy available for society in rapid transition scenarios may result in a high investment share and employment rate in low-emissions technologies, which could altogether generate inflation [7,45,46], and thus raise questions of socio-political acceptance.

The pace of transition is bounded at the upper limit by the energy needed to sustain society without disruption (additional supply bottlenecks aside), and at the lower limit by the minimum speed required to meet climate targets (see Figure 3). Both limits are expected to move closer to each other as the transition is delayed, reducing the window of opportunity for a global transition compatible with ambitious climate targets. On one hand, the upper limit is likely to become more restrictive over time due to the geological depletion of fossil fuels, the fact that a more rapid low-carbon investment consumes a higher proportion of energy, and that more high-carbon investment needs replacement or becomes stranded. On the other hand, the lower limit will become more pressing because, trivially, the longer the transition delays, the less likely it is to comply with ambitious climate targets. The implementation of demand-side policies [47] to reduce discretionary energy use, as highlighted by IPCC WG III [1], is becoming increasingly relevant in this regard. Moving away from unnecessary uses and switching to more efficient conversion chains (e.g., from gasoline-powered to electric cars or bicycles) helps reduce discretionary energy use as long as rebound effects are mitigated. Further, recent research suggests that a decent life for all can be sustained at much lower levels of final energy use than at present within wealthy nations [48–50].

The energy transition has implications for equity. In particular, the upcoming reductions in net energy will necessarily amplify energy transition costs due to fossil fuel inflation and rapid low-carbon investment. Such reductions will in turn exacerbate competition for the energy and material resources necessary for the transition, a competition in which low-income countries are already at a clear disadvantage [51]. Every Northern country that delays action thus risks compromising its ability to complete a transition and maintain or achieve high levels of material well-being, both for itself and other countries. This political situation raises inequity issues as countries from the Global North are likely to make their transition first. In this context, countries of the Global South are susceptible to lack access to energy, to the risk of getting slowed down – or even trapped – in their progress towards modern low-carbon energy, while being among the least responsible for and most affected by climate change [52–56]. Accelerating the energy transition for the Global South is therefore a major stumbling block to a "just" transition, and requires massive financial support and technology transfers [57–60].

Proper consideration of net energy is required in mitigation pathways

While significant progress has been made in research on mitigation pathways, net energy has been addressed only marginally. The latest IPCC report [1], for instance, mentions EROI issues in one paragraph (ch. 6, p. 44) and leaves out the evolution of the related literature, in part because the 8 key points developed earlier have only recently emerged. This situation results in insufficient discussion on the consequences of a decrease in the EROI of the energy system. The overlooking of net energy is also apparent in Integrated Assessment Models (IAMs), the main tools used to produce global, regionally disaggregated mitigation pathways [61].

First, most IAMs merely characterize exhaustible fossil fuel resources through cost-supply curves, whose limitations in terms of modeling and parameterization lead to significant loss of robustness for mitigation pathways. On one hand, these curves operate under the assumption that the supply of fossil fuel resources depends purely on economic criteria, which means that production fluctuates with price, but in reality prices increase also because production does not increase fast enough. They furthermore assume that the most economically viable reserves will be exploited first, regardless of the complex interplay of other socio-geopolitical factors that shape the reality of producing companies [62], countries [63], and regions [64,65]. On the other hand, typical upward sloping cost-supply curves are subject to criticism for potentially outdated, simplistic and over-optimistic assumptions in the recoverability of fossil resources [5,66–85]. For instance, the MESSAGE [86] and IMACLIM-R [87] (partly) models continue to depend on the data provided by Rogner et al. [88] for global fossil fuel reserves and resources, while the EPPA model [89] includes simple recursive endogenous resource supply functions. The use of cost-supply curves also impedes the analysis of the economic consequences of a plateau or decline in oil production [90]–for example left out in the EMF27 [91] and RoSE [82,92–94] intercomparison exercises. The main problem of using technically simplistic and methodologically questionable cost-supply curves is not only overestimating the plausibility of high-emission scenarios,

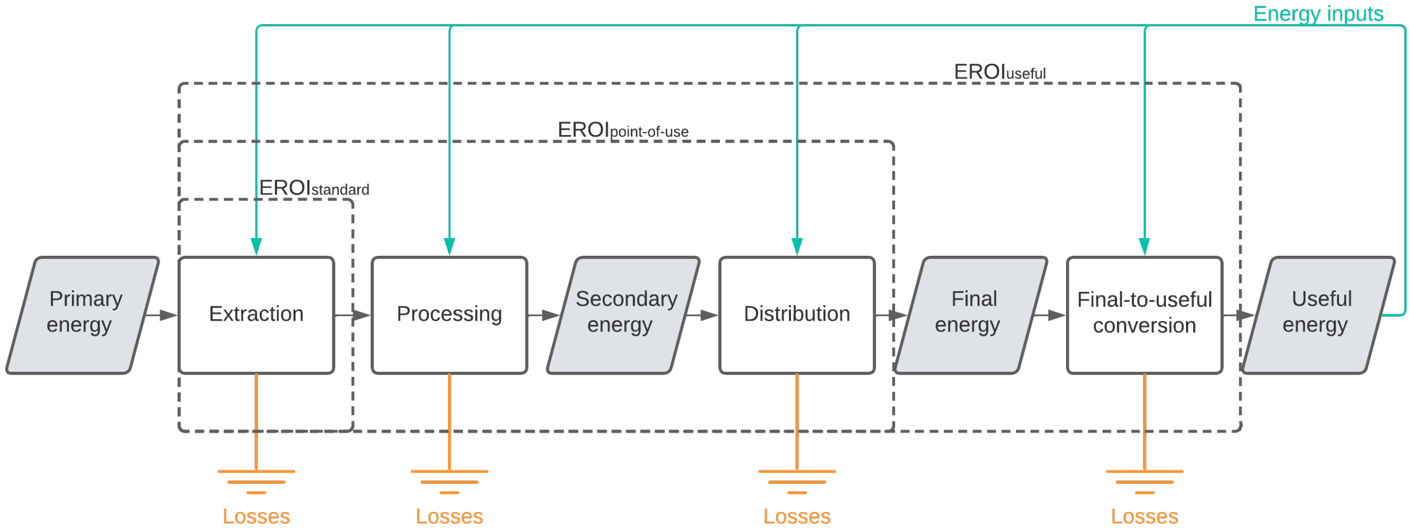

Fig. 2 Standard, or primary stage EROI ($EROI_{standard}$), point-of-use or final stage EROI ($EROI_{point-of-use}$) and useful EROI ($EROI_{useful}$).

but also making fossil fuels more attractive than they would be if depletion feedback effects were properly considered. This point of view is supported by the evaluation of AR5 scenarios against consistent growth rates of emissions from the fossil fuels industry[95,96], and the analysis of the GCAM-MAGICC integrated assessment model's sensitivity to revised cost-supply curves[83]. It is also backed by the comparison of WoLiM[78,97] or MEDEAS[5] energy-constrained model results with scenarios from the literature, the incorporation of thorough oil production profiles in IMACLIM-R[98,99], and the examination of various fossil resource availabilities in the RoSE exercise.

Another critical modeling assumption is the fact that the energy used by the industry for a given scenario is not calculated in relation to the demand for the raw materials necessary for the completion of that scenario. To be able to calculate the raw material requirements, IAMs would have to represent the stocks of all infrastructures, combined with data on lifetimes and material intensities. The potential inconsistency between the industrial energy calculated from elasticities in IAMs and the industrial energy that would be calculated using a stock and raw materials approach adds further uncertainty to the net energy requirements[100,101].

Moreover, IAMs dismiss comprehensive energy-economic feedbacks. They indeed assume that decreasing (net) energy supply, or increasing energy costs, do not influence economic growth whatsoever, as in the IMAGE[102], GCAM[103] or POLES[104] models, or have minimal impact when the output is recursively calculated, for instance using nested constant elasticity of substitution (CES) production functions found in models like EPPA, GTEM-C[105], REMIND, and WITCH[106]. These functions have indeed faced criticism for their inability to accurately align with historically observed patterns in the dynamics of energy transition[107,108]. We find this lack of energy-economic feedbacks particularly troublesome as the decrease in the EROI of the energy system will influence the impact of make demand-side measures in mitigation scenarios. The lack is even more problematic since some authors have found that IAMs favor Bioenergy with Carbon Capture and Storage (BECCS) over the use of renewable energy, notably by underestimating the cost reduction potential of renewables and especially PV[109–114], while in fact bioenergy and CCS technologies result in a significant decline in net energy[115,116]. The importance of the net energy-economy feedback becomes even more apparent when considering the substantial energy requirements associated with the deployment of Direct Air Carbon Capture and Storage (DACCS), which are estimated to consume up to 300 EJ/yr by 2100 in some scenarios[117].

A considerable exception to current IAMs is the MEDEAS model[5,119,120]—now developed as the WILIAM model in the scope of the LOCOMOTION project—which appears to be the sole multi-scale‡ IAM that explores, from a heterodox perspective[123], the implications that the energy required for the transition may have on the energy system and the economy[124]. Unlike other IAMs, MEDEAS includes an energy-economy feedback that allows energy availability to limit GDP growth in the event that it falls short of demand[123]. When compared with AR5 business-as-usual scenarios, the results obtained with MEDEAS show a larger primary energy intensity of GDP, as well as lower CO_2 intensity of primary energy, GDP per capita, and temperature change over pre-industrial levels[5]. Such a modeling approach not only enables the characterization of the interaction between energy and the economy, such as the rebound effect[125], in a more historically consistent way[126], but also allows the user to assess the probability of GHG scenarios taken from other IAMs[127], as well as degrowth scenarios[123,125,128].

The reasons why net energy is not comprehensively accounted for in IAMs are multiple and, in our view, fall primarily into three categories.

† In this regard, it is worth noting that it has been estimated that, due to residual fossil emissions, 640–950 $GtCO_2$ carbon dioxide removal (CDR), i.e., BECCS, DACCS and afforestation, will be required for a likely chance of limiting end-of-century warming to 1.5°C, when strengthened pre-2030 mitigation action is combined with very stringent long-term policies[118].

‡ The SFCIO-IAM[121] and WORLD7[122] are for instance only global models.

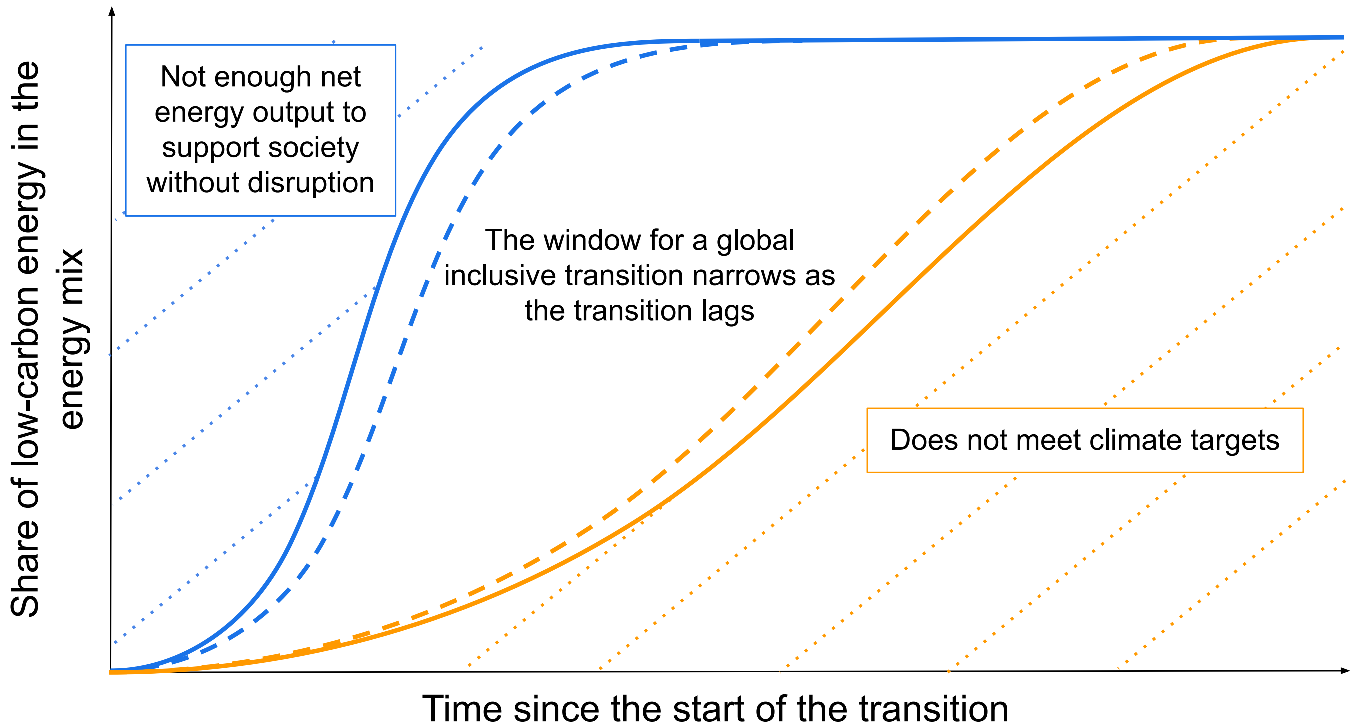

Fig. 3 Sketch of principle of an evolving window of opportunity for the global inclusive transition to low-carbon energy as a function of normalized time at the start of the transition. The solid lines delineate the current window of opportunity. The dashed lines represent a future window in which action has not been taken quickly enough such that climate and net energy increasingly constrain the window of opportunity.

First, most IAMs lack proper representation of the energy and material flows of the goods and services provided[129–131], making them structurally unable to consider the industrial energy embodied in the infrastructures, and thus the energy-economy linkages brought to the fore by net energy analysis. Overlooking these flows may lead to an overestimation of the potential for reducing energy intensity (thus assuming possibly unrealistic decoupling rates between GHG and energy/material use), a greater focus on supply-side solutions for mitigating climate change[132], and underestimating the impact of rebound effects on energy demand[41,125,133–135].

Second, most IAMs – either energy system models coupled with macroeconomic growth models or multi-sectorial Computable General Equilibrium (CGE) models – still utilize optimal growth theory from neoclassical economics. However, in these models, increases in energy costs cannot significantly affect GDP growth, either because GDP or technological change are assumed to be exogenous, or because the cost share of energy (as a percentage of GDP) is assumed to have negligible feedback on GDP. Thus, the current crop of IAMs not only downplays the contribution of energy and exergy in economic processes[136–138], but also sets aside its interaction with money and the financial sector, as these are both largely unmodeled in IAMs[139–142]. This omission further precludes any attempt to understand how high levels of debt, which can increase financial instability risks, can be associated with net energy constraints or high energy costs (e.g. the global financial crisis of 2007-2008)[143].

Third, the current climate change scenarios framework (illustrated by the Shared Socioeconomic Pathways, SSP[144]) nurtures a simplistic and technocratic vision of the economy, that assumes little in the way of interdependence among population, economic growth, and other socio-economic parameters such as net-energy[145–151]. This lack of explicit interdependence hinders existing climate mitigation scenarios from adequately assessing societal transformations[152], (in)justice[153–155] including large-scale shifts in energy use between Global North and South[56], and systemic risks[156]. The roots of the aforementioned limitations can be found in a lack of reflexivity, imaginative flexibility, plurality, transparency and transdisciplinarity within the IAM community, as acknowledged by some of its own members[130,157–166], but also in the gradual erosion of IAMs' neutrality[167,168] due to political influence, and the community's interest in playing an increasingly normative role in climate governance and policy-making[169–171].

Avenues of improvement to consider net energy in IAMs

Several initiatives are underway to better account for industrial energy, and represent the interactions between energy and the economy in macroeconomic models and/or IAMs[172]. Some IAMs, for instance, have adopted the use of more reliable data pertaining to fossil fuel energy resources, as exemplified by the incorporation of a comprehensive bottom-up dataset from Rystad Energy in E3ME-FTT-GENIE[173,174] or the construction of detailed field-level analysis supply curves in TIAM-UCL[175]. Dynamic constraints on extraction rates have also been introduced, as in REMIND[176] or TIAM-UCL[177] models, as well as specific rules trying to mimic the behavior of swing producers, as in IMACLIM-R or IMAGE, albeit in a very simplified way and mostly for the oil market[178,179]. In an attempt to bridge the gap with Industrial Ecology (IE), several IAMs (notably REMIND and MESSAGE) have explored the implications of incorporating life cycle assessment coefficients from input–output (I–O) tables such as THEMIS[180–182] or EXIOBASE[183], highlighting the potential for sustainability research areas such as the energy-industry nexus and post-growth scenarios[184]. Efforts are also underway for examining the contribution of improved Energy System Models (ESM)[185,186]. Still, most IAMs operate within the neoclassical equilibrium framework, and thus do not properly capture the feedback from the energy system on the economy. For instance, Pehl et al. (2017)[180] integrate a life-cycle assessment perspective in the REMIND model, and find that "fully considering life-cycle greenhouse gas emissions has only modest effects on the scale and structure of power production in cost-optimal mitigation scenarios". However, the authors rely on a model that uses a CES production function, with limited feedback from the energy system (including its energy requirements) on the economy, and focus exclusively on the power sector.

In an attempt to remedy this situation, we highlight six avenues for improving IAMs:

1. the integration of Industrial Ecology methods (e.g. Material Flow Analysis) or modules such as DyMEMDS[187–189], ODYM-RECC[190,191], or QTDIAN[192], in order to better capture stocks and flows of energy and materials associated with the industrial subsector;

2. the adoption of a multi-sectoral energy framework, for instance relying on primary-final-useful (PFU) energy databases[193–196] and consistent energy services narratives;

3. the use of an ecological macroeconomic framework (as in HARMONEY[197,198] or TranSim[199]) or ESM which deal with environmental and biophysical indicators[200] in a more comprehensive way, such as ENBIOS[201], EnergyScope[202] or the one developed by Crownshaw[203];

4. a common reporting template to include the energy consumption of the energy sector as well as useful energy in mitigation scenarios[8,204,205];

5. an explicit modelling of energy-economy feedbacks (including rebound effects) using net energy, at least with the aim of understanding how a net energy feedback would affect IAMs results to assess to what extent energy and economic feedbacks are internally (in)consistent across mitigation pathways[205];

6. the exploration of new mitigation pathways achieving high wellbeing levels with low resource use[206], limiting the deployment of energy intensive carbon dioxide removal[121,207–210], and equitable low-growth[211] and post-growth scenarios[212–219].

However, if these measures are to be properly implemented, they must be carried out simultaneously and without neoclassical economics theories[220,221], which we see as incompatible. This point particularly addresses the IAM community's appeal that "further studies should at least aim at better reflecting the plurality of the visions of the economy"[172] and take advantage of the robust development of heterodox economics[222], especially ecological macroeconomics[223,224].

As countries seek to develop new nationally determined contributions (NDCs) and the IPCC currently considers reforming itself to produce more relevant knowledge for climate action[225–227], current momentum is towards the development of a new generation of IAMs and scenarios[228–235]. In this regard, we believe that fostering collaborative efforts among our different research communities is timely, and could help improve integrated assessment modeling, with these dynamics being all the more supported by the convergence of views on demand-side measures and alternative economic pathways.

Conclusion

Consideration of net energy is crucial to assess and design comprehensive and coherent climate mitigation scenarios. Yet, in part due to the late emergence of robust results in the EROI literature, such consideration has not yet spread beyond the Net Energy Analysis community. Here we try to address this issue by outlining the emerging EROI consensus, exploring key areas under investigation, and identifying further work.

Our summary underlines that, in a fossil fuel dominated world, the initial energy investment to power the transition to a low-carbon future will inevitably come from fossil fuels. This does not mean, though, that renewables cannot eventually support themselves. However, net energy constraints may still limit the energy available to invest in energy infrastructure and the energy available for discretionary uses, absent more sustainable production and consumption habits. This situation may be particularly destabilizing for industrializing countries, which might stay at the doorstep of the energy transition, unable to increase their reliance on modern low-carbon energy, while being among the least responsible and among the most impacted by climate change. These dynamics should not be ignored in transition scenarios, and we therefore call on fellow researchers to integrate net energy into Integrated Assessment Models using theories outside of the neoclassical economics paradigm. In this respect, we believe that fostering collaborative efforts among our different research communities could prove decisive.

Acknowledgments

This work benefited from the careful reading of Paul Brockway, Jarmo Kikstra and Loïc Giaccone. We also thank Iñigo Capellán-Pérez for comments on a previous version of the manuscript. Louis Delannoy, Pierre-Yves Longaretti and Emmanuel Prados acknowledge the support of the French National Institute for Research in Digital Science and Technology (INRIA). Victor Court acknowledges the support of the Chair Energy and Prosperity, under the aegis of La Fondation du Risque.

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Conflicts of interest

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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