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Dynamic EROI of the global energy system in future scenarios of transition to renewable energies

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ABSTRACT

The transition from fossil fuels to Renewable Energy Sources (RES) is an indispensable condition to achieve sustainable socio-economic systems. Despite their indisputable environmental benefits, their technical performance can be, in some cases, worse than those of fossil fuels. This is the case of the Energy Return on Energy Invested (EROI). Much work has been carried out to estimate the EROI of individual RES technologies; fierce debates about methodological issues are still not closed. In this work, we approach this issue by dynamically estimating the EROI of the whole energy system in future scenarios of transition to renewables. For this, we apply the global MEDEAS-World simulation model, which computes the dynamic EROI (standard, EROIst) of individual renewable technologies as a function of the associated energy requirements to build the infrastructure (construction phases and materials). The EROI point of use (EROIpou) of the whole energy system is obtained taking into account the additional energy investments to cope with RES intermittency (i.e. storage, overcapacities and overgrids) as well as the related distribution energy losses. Two scenarios up to 2050 are simulated: (1) Business-as-usual (BAU, continuation of current trends) and (2) “Green Growth” (GG, higher economic growth, faster transition to RES, higher efficiency improvements, etc.). The contribution of RES in the energy mix increases from ~15% to over 30% in BAU and almost 50% in GG by 2050. This penetration of RES technologies in the energy mix translates into a decrease of the EROIpou of the whole energy system from current 6:1 to 5:1 (BAU) and below 3:1 (GG) by 2050. These results put into question the viability of the Green Growth paradigm as it is being currently presented.

KEYWORDS

Energy Return on Energy Investment; high penetration of renewables; energy trap; Green Growth; integrated assessment modelling

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1. INTRODUCTION

The transition from fossil fuels to Renewable Energy Sources (RES) is an indispensable condition to achieve sustainable socio-economic systems. Despite their indisputable environmental and social benefits (e.g. lower pollution [1] and the possibility to be managed at local, participative level [2]), the technical performance of RES technologies can be, in some cases, worse than those of fossil fuels. In fact, fossil fuels are characterized by favorable physical-chemical properties (e.g. high power density, storable, inert at standard ambient conditions, etc.) that allow manageable, high-quality energy flows to easily supply human societies. In contrast, RES technologies generally require more land surface (i.e. lower power density, [3–5]), their use competes with other processes of the biosphere REF, while those with a higher potential (i.e. wind, solar) are critically affected by their intermittence and variability [4,6,7] and have been generally found to have lower Energy Return on Energy Invested (EROI), the energy delivered from a process divided by the energy required to get it over its lifetime, than fossil fuels [8,9]:

$$EROI = \frac{energy\ returned}{energy\ invested}$$

Considering the EROI allows to take a “net energy” approach in energy systems analysis, which represents a number of advantages in relation to the conventional “gross energy” approach: the relevant dimension is the energy available to the society (not the energy produced by power plants) [10–12], internalization of factors that affect the whole energy system that are not captured by the monetary costs of individual power plants (such as the additional costs for the system related with distribution, intermittency of RES, etc.) [13–18]; and detection of potential harmful situations of increasing gross energy output while decreasing the net energy delivered to the society, i.e. the so-called “energy trap” [19,20].

Much work has been carried out to estimate the EROI of individual RES technologies [9,21–24]; however important differences exist depending on the technology, system design and location, and the field is plagued with methodological discrepancies related with the functional units (e.g., a megajoule of heat energy versus a megajoule of grid electricity) or the boundaries of the analysis (i.e. mine-mouth vs end use or energy technology vs energy system) [11,25–29]. From a societal/metabolic point of view, the relevant dimension is the energy available to the society (not the energy produced by power plants). In fact, a favourable EROI over the long-term has been identified as an historical driver of evolution and increasing complexity [10–12]. Societies with high EROIst values are generally more prosperous, given that more energy is available for discretionary purposes relative to that which must be reinvested in the energy sector and basic maintenance [30]. [31] and [32] calculated that discretionary economic production drops rapidly when EROIst falls below 5:1. Therefore, for a society to be prosperous, the EROIst of its energy sources should be much greater than 5:1. [33] estimated that an EROIst of 10–15:1 is the minimum EROIst needed for modern industrial consumer societies to support such things as modern healthcare, education, and arts (discretionary spending) in addition to basic needs (e.g., food, shelter, and clothing), a result similar to the one obtained by [17].

Thus, it is of key importance to understand the socioeconomic consequences of the large-scale replacement of fossil fuels with RES. The energy transition to renewable resources and new energy conversion and storage devices will affect the fraction of energy reinvestment available for discretionary economic production [14,16,17,34], even having the potential to create scenarios known as of “energy trap”, which may imply a reduction of the net energy available to society if the construction of new infrastructure grows too rapidly [20,34].

The literature review reveals that recent work has been directed to estimate both (1) the historic evolution EROI of national energy systems, and (2) the EROI associated to high RES penetration scenarios. A diversity of methodologies is being applied, including proxy methods based on economic data [33,35], input-ouput tables [36], optimization of electricity mix [37]; some including storage in the framework such as [13] and [18].

The aforementioned studies apply the EROI as a static concept, i.e. assuming that the energy invested is proportional to the energy obtained along the lifespan of the functioning power plant. However, power plants require, in fact, energy investment upfront to construct, providing energy returns only over the lifespan of the facility. This representation worsens the negative implications of potential energy trap scenarios. In this sense, different works have focused on the dynamic integration of EROI to obtain more realistic results [19,34,38,39].

Here we present the developed methodology to implement the net energy approach in the MEDEAS simulation model, a global energy-economy-environment system dynamics model focused on the biophysical dimensions and interactions of the transition towards RES [40]. This model, which computes the dynamic EROI (standard, EROIst) of individual renewable technologies as a function of the associated energy requirements to build the infrastructure (construction phases and materials). The EROI point of use (EROIpou) of the whole energy system is obtained taking into account the additional energy investments to cope with RES intermittency (i.e. storage, overcapacities and overgrids) as well as the related distribution energy losses.

A variation in the EROI of the energy system has implications for the rest of the energy-economy-environment system. However, this has been very rarely taken into account in the literature. In this sense, having the energy system embedded in the whole biophysical and socio-economic system as considered in MEDEAS allows to account for the net energy actually available for the society, and its implications for the rest of the system.

As it will be shown in the paper, this novel dynamic, energy-systems approach, allows to reconcile some of the extant methodological discrepancies currently existing in the field.

2. METHODOLOGY

The representation of the net energy approach in the MEDEAS model includes 5 key novelties which significantly improve the current state-of-the-art of the field:

1. Endogenous calculation of the EROIst of individual technologies taking as a starting point the materials required in the construction, operation and maintenance phases as well as their recycling rates [41],
2. Dynamic and endogenous representation of the EROIst of individual technologies accounting for the up-front costs per technology as well the configuration of the energy mix (i.e. requirement of overcapacities to deal with intermittency in high RES penetration scenarios),
3. Allocation of technologies based on their relative EROIst (higher EROI technologies tend to cover a larger share of the energy capacity demand).
4. Computation of the EROI of the whole energy system (including overcapacities, storage and overgrids),
5. Incorporation of the implications of the variations in the EROI of the system for the total final energy demand.

An extensive literature review has been performed to identify the materials required to construct, operate and maintain the so-called “scalable” RES technologies for electricity generation, i.e. (solar CSP, solar PV, wind onshore and wind offshore), i.e. those renewable sources characterized by a higher techno-sustainable potential [42,43]. Two more technologies are considered in this bottom-up assessment of material requirements which are also considered key for the large-scale deployment of RES: electric batteries and overgrids. This way, requirements for a total of 58 materials have been reviewed (of which 19 minerals). This approach allows to endogenize the EROIst of each technology depending on the recycling rate of the minerals (the energy consumption per unit of material consumption is very different depending on the fact if the material is virgin or recycled). The applied methodology is fully documented in [41].

In relation to the estimation of EROI of the system, it is not appropriate to approach the question by using estimates of "buffered" EROIs for each renewable technology (as done for example by [44] considering pumped hydro storage for wind and solar PV) given that these values are of little or no use given that energy systems are designed so that different technologies can partially complement and substitute for each other [45]. In this work a step further is performed in relation to previous works by jointly considering the implications of complementarity and intermittence of different RES sources for the EROI of the system. This way, the required overcapacities, storage and overgrids are not assigned to a particular technology but to the whole energy system.

Two scenarios are simulated in MEDEAS global model to 2050 in order to illustrate the importance of considering all the aforementioned factors in the planning of the transition towards a low carbon economy: (1) Business-as-usual (BAU, continuation of current trends) and (2) "Green Growth" (GG, higher economic growth, faster transition to RES, higher efficiency improvements, etc.). We select the GG paradigm as alternative scenario to current trends given that key global international organizations have embraced these concepts including the World Bank, the UNEP, the OECD, the European Commission and it is the center of debate in international forums [46–51]. In a word, it is the alternative paradigm assumed by the establishment to avoid the adverse impacts on human societies of the global environmental change.

2.1. EROIpou of the system

Ideally, the concept of EROIext should be used when assessing systemic implications of the variation of EROI over time. However, the practical estimation of EROIext is very complex and subject to many uncertainties. To date, few studies have attempted to evaluate it estimating the economic costs associated with the construction of the energy system, and using average energy intensities to transform to energy inputs (e.g. [26,28]). This methodology is questioned by other authors, which prefer to assign a "zero" energy cost to those categories.

Here we take a conservative approach estimating the EROI of the system from both a standard ($EROI_{system}^{st}$) and point-of-use ($EROI_{system}^{pou}$) approach.

Different energy flows and conversions are required in the social metabolism in order to make available final energy to the society:

(1) Useful energy used by society

(2) direct (i.e. on site) and indirect (i.e. offsite energy needed to make the products used on site) energy requirements to build, operate, maintain and disposal the plant of energy generation.

(3) Additional energy requirements so the system correctly handles RES intermittency

(4) Distribution losses

(5) Energy requirements to build the machines and infrastructure required to construct the capital which allows to make the energy investments (2), (3) and (4)

Attending to the definition of standard EROI, the EROI of the system is defined as the ratio between the final energy delivered to society and the energy required for the production of energy vectors ($EROI_{system}^{st}$):

$$EROI_{system}^{st} = \frac{(1)}{(2)}$$

If including more factors such as distribution losses and the additional energy requirements so the system correctly handles RES intermittency, i.e. extending the boundaries, the EROI of the system from a "point of use" approach ($EROI_{system}^{pou}$) can be defined as follows:

$$EROI_{system}^{pou} = \frac{(1)}{(2) + (3) + (4)}$$

The following assumptions are taken to compute the $EROI_{system}^{pou}$:

1. For the sake of simplicity, the EROIst of non-renewable energy sources (oil, gas, coal and uranium) is assumed to be constant over time. This simplification can be considered as conservative, given that in the long term the EROI of these fuels will tend to decrease. Indeed, recent analyses have found that the trend is already decreasing for fuels such as oil and gas [9,52].
2. The EROIst is dynamically estimated for renewable technologies for the generation of electricity. The EROIst of other renewables such as liquid biofuels or technologies for heat generation is considered to be constant over time.
3. Overgrids and overcapacities related to the increasing penetration of variable renewable technologies in the system are endogenously obtained in the model. Overcapacities reduce the effective CF of each technology decreasing its EROI. Overgrids are modelled as an additional component of the material intensity (kg/MW) each technology as described in [41].
4. Additional storage losses are modelled following [13]. The reduction of EROIst at grid scale depends on the ratio of electrical energy stored over the lifetime of a storage device to the amount of embodied electrical energy required to build the device (i.e. an analog to EROI for storage technologies, the Energy Stored on Energy Invested (ESOI)); a certain level of curtailement (φ) and the efficiency of the electric storage (η).

A step further, at least conceptually, would be to accounting for the energy requirements to build, operate, maintain and dispose the machines and infrastructure (5) required to make the energy investments (2), (3) and (4). This way we would arrive to an "extended" definition of the EROI of the system:

$$EROI_{system}^{ext} = \frac{(1)}{(2) + (3) + (4) + (5)}$$

2.2. Modelling framework of MEDEAS

MEDEAS-World (MEDEAS-W) is a global, one-region energy-economy-environment model (or integrated assessment model). It is a simulation model which has been designed applying

System Dynamics,[1] which facilitates the integration of knowledge from different perspectives and disciplines as well as the feedbacks from different subsystems. The model typically runs from 1995 to 2050 (although the simulation horizon may be extended to 2100 if necessary, e.g. when focusing on climate change issues). MEDEAS-W is structured into seven main submodules: Economy, Energy, Infrastructures, Materials, Land Use, Social and Environmental Impacts Indicators and Climate Change (see Figure 2). The main variables that connect the different modules are represented by arrows.

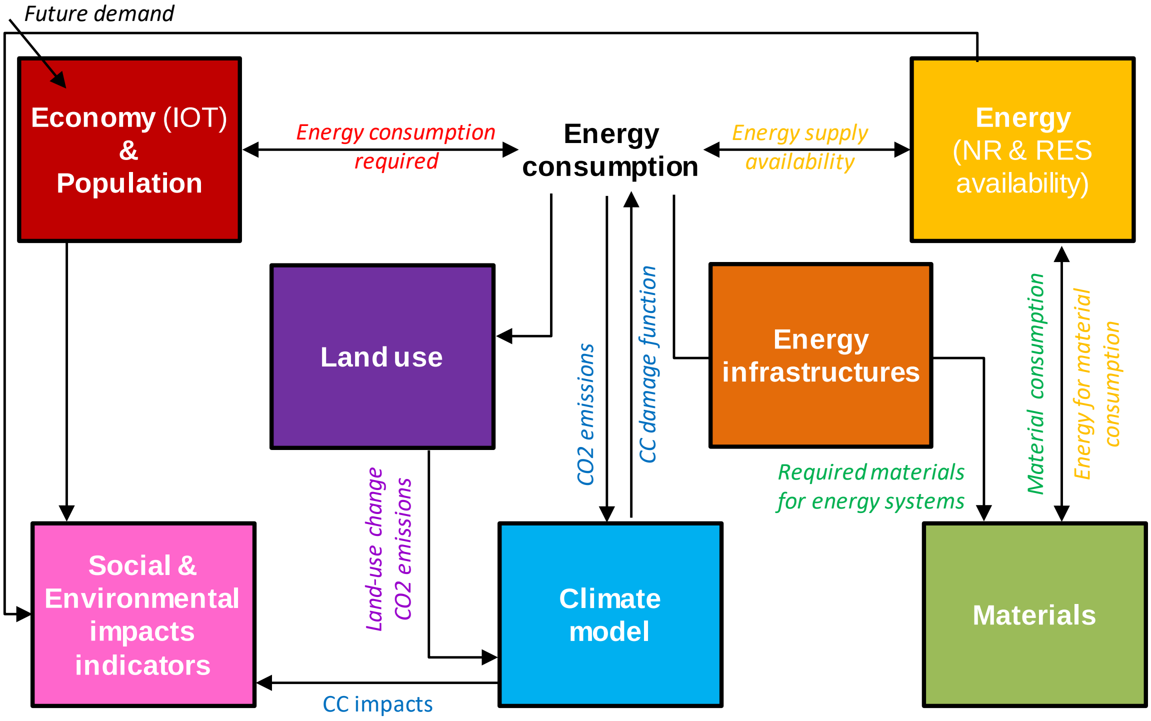

Figure 1: MEDEAS-World model schematic overview. Source: [40].

The main characteristics of each module are:

- Economy and population: the global economy in MEDEAS is modelled following a post-Keynesian approach assuming non-clearing markets (i.e. not equilibrium) and demand-led growth, combined with supply-side constraints such as energy availability. The economic structure is captured by the dynamic integration of global WIOD input-output tables which include 35 industrial sectors and households [53]. Final energy intensities by sector are obtained combining information from WIOD environmental accounts [54] and the IEA Balances (2018). Population evolves exogenously as defined by the user. See [56] for more details on this submodule.
- Energy: this module includes the renewable and non-renewable energy resources potentials and availability taking into account biophysical and temporal constraints. In particular, the availability of non-renewable energy resources depends on both stock and flow constraints [57–59]. In total, 34 primary energy sources and 5 final fuels are

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[1] Developed in Vensim DSS software for Windows Version 6.4E (x32). Also available in Python open-source code. Both codes are available in http://www.medeas.eu/.

considered (electricity, heat, solids, gases and liquids), with large technological disaggregation. The intermittency of RES is considered in the framework, computing endogenous levels of overcapacities, storage and overgrids depending on the penetration of variables RES technologies. A net energy approach accounting for the EROI of both individual technologies and the EROI of the system is applied. This submodule is mainly based on the previous model WoLiM [60]. Transportation is modelled in high detail, differentiating between different types of vehicles for households, as well as freight and passenger inland transport (see [40] for details).

- Energy infrastructures represent power plants to generate electricity and heat, allowing to consider planning and construction delays.
- Climate: this module projects the climate change levels due to the GHG emissions generated by human societies (non-CO2 emissions are exogenously set taking as reference RCPs scenarios [61]). The carbon and climate cycle is adapted from C-ROADS [62,63]. This module includes a damage function which impacts sectors' economic output depending on the level of global temperature change [64].
- Materials: materials are required by the economy with emphasis on those required for the construction and O&M of alternative energy technologies [41]. Option of recycling policies.
- Land-use: this module currently mainly accounts for the land requirements of the RES energies.
- Social and environmental impacts: this module translates the "biophysical" results of the simulations into metrics related with social and environmental impacts. The objective of this module is to contextualize the implications for human societies in terms of well-being for each simulation.

The model dynamically operates as follows. For each period: firstly, a sectoral economic demand is estimated from an exogenous and dynamic GDPpc objective. Using energy-economy hybrid Input-Output Analysis, and combining monetary output and energy intensities by final energy sources, the final energy demand required to meet economic demand is obtained. Secondly, the energy submodel computes the net available final energy supply, which may satisfy (or not) the required demand: the economy adapts to eventual fuel scarcity. Thirdly, materials required to build, operate, maintain, dismantle, etc. are estimated. This allows to estimate the EROI of the system as well as to assess eventual material bottlenecks (although material availability does not constrain economic output in current model version). Fourthly, the climate submodel computes the GHG emissions, whose accumulation derives into a certain level of climate change, which in turns feed-back the economic output. Land and water additional requirements are accounted for. Finally, social and environmental impacts are translated from the biophysical results. This way, MEDEAS incorporates two limits to growth that are rather rarely considered (even separately) in the literature: consistent climate change impacts and energy availability (which interact with the variation of EROI level of the system).

For a detailed documentation of the MEDEAS-World model, see [40].

3. RESULTS

Figure 3 shows the dynamic evolution up to 2050 of the EROIpou of the system obtained in the simulation of the BAU and GG scenarios with MEDEAS-W model. The obtained results reveal that, under the applied assumptions, the current EROIpou of the system is ~6:1 values, and that it has decreased from ~7:1 since 1995.

In BAU scenario, this trend continues reaching a value of 5:1 by 2050, due to the slight penetration of RES in the system (which almost reaches 30%, doubling its current contribution to the total primary energy supply –TPES-). In GG scenario, the fastest pace of penetration of RES technologies (which almost reach 50% of TPES by 2050, drive the EROIpou of the system to values below 3:1.

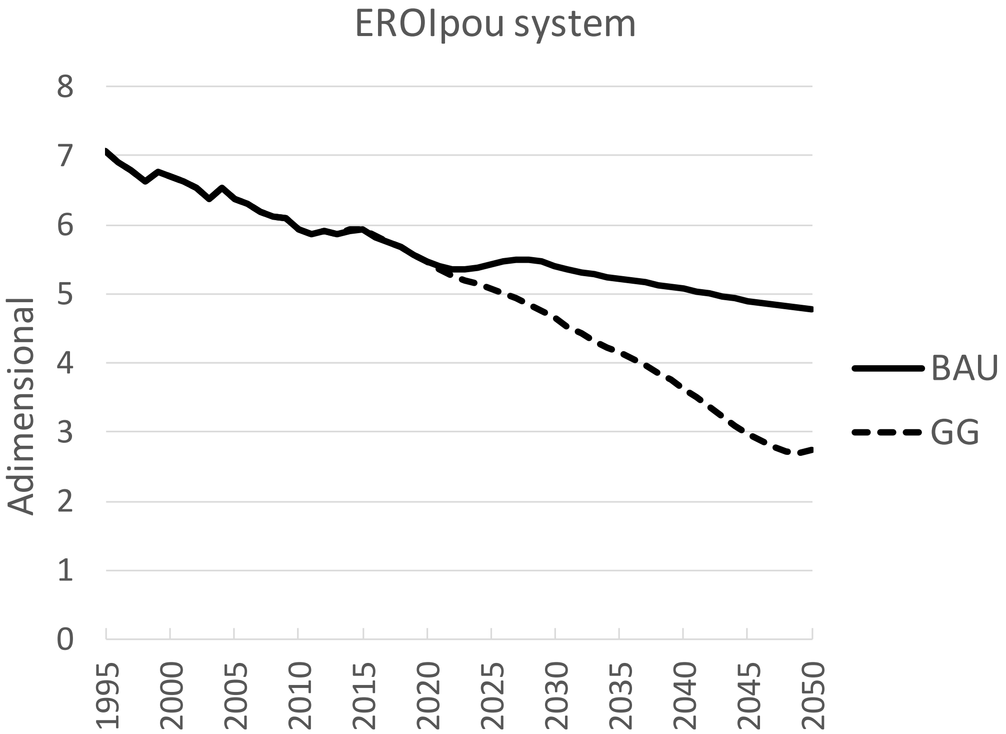

Figure 2: Dynamic evolution of the EROIpou of the energy system for scenarios BAU and GG.

The reduction in the EROI of the system has implications for the rest of the system: in order to satisfy the same level of final net energy consumption, the system needs to process more energy and materials to make it available for the society. This phenomenon is modelled in MEDEAS-W through a function of overdemand. In BAU scenario, the overdemand does not represent significant levels and remains below +2% in almost all the simulated period. However, in scenario GG, overdemand skyrockets over the period almost reaching +25% by 2050. This means that, in order to satisfy the same final net energy demand, the system needs to process 25% more of energy.

The additional increase of final energy demand related with the deployment of RES in GG scenario has also important implications for the efficiency of the system. In terms of final energy intensities, this effect has the potential to counteract the effect of higher exogenous efficiency improvements which are assumed in this scenario. It is noteworthy that when computing the total final energy intensity without the feedback of the EROI of the system, the total final energy intensity steadily decreases over the simulated period, while including the feedback produces a rebound in this metric in the 2040 decade which points towards a rematerialization of the economic system caused by RES penetration in the mix.

4. CONCLUSION

The obtained results show that net energy analysis is key to correctly model the transition towards energy systems based on RES. In this sense, findings from previous works are confirmed [13,15,18,34]. Renewables at low market penetration represent relatively low integration costs for the full energy system. However, as the penetration increases and displaces conventional dispatchable fuel sources, the energetic costs associated with the required overcapacities, overgrids and storage substantially reduce the EROI of the whole system due to energy requirements for both construction and operation of the modified energy system. In particular, the obtained values below 3:1 for the EROIpou of the system in the Green Growth scenario are below the thresholds identified in the literature to sustain high levels of development (<10:1 Hall et al., [17,28], <5:1 [32]). This result puts into question the viability of the Green Growth paradigm as it is being currently presented. In fact, one the key assumptions of this narrative, i.e. the absolute decoupling of economic growth in relation to energy use, is showed not to be consistent with the levels of material and energy required to perform the energy transition towards RES.

From a methodological point of view, this works presents a number of novel contributions in relation to the state-of-the art of energy systems analysis and EROI, allowing to reconcile some of the extant discrepancies in the literature [11,25–29]: (1) the dynamic approach allows to overcome the limitations of the common static approaches; and (2) the required overcapacities and storage in high RES penetration scenarios are not assigned to any specific technology, but rather to the whole energy system.

The computation of both the EROI of the system and the EROI-based allocation of RES technologies in the energy mix represents a key novelty in relation to the current modelling state of the art. Virtually all models used for policy-advice are based on gross energy output and rely on price-based allocations methods (e.g. IEA, IPCC, national governments, etc.). To our knowledge, very few models take a net energy approach (GEMBA [65]; NETSET [39], and even less are the studies considering the allocation of technologies depending on their relative EROI (e.g. [37]). However, it should be keep in mind that the EROI does not capture all the benefits and disadvantages of a given technology. For example, in the case of rooftop PV, despite its lower efficiency in relation to ground-based plants, it does not require additional land.

As any modelling study, this work presents a number of limitations. These may be addressed in further work. For example, the implications of the drop of the EROI of the system to very low levels are not fully captured in the current framework. In reality, if the system does not include « inteligent/correcting controls » a sharp drop in the EROI of the system to such low levels should endogenously induce a collapse of the system (as for example in [32], where the model allows to endogenously estimate the relevant EROI threshold). An option would be to consider the link between the energetic investments in the energy module and the related monetary investments in the Economy module (as performed by [34,65]).

Further work may deepen the study of the allocation of energy technologies depending on their relative EROI. This would allow to improve the criteria for successfully planning the transition to RES. From the point of view of material availability, given that the model tracks the material consumption of alternative technologies, further work could be directed to the analysis of the implications for potential material bottlenecks in the context of transition to RES (e.g. [66–69]). Further work may also be directed to explore alternative ways to analyse the implications of the evolution of the EROI of the energy system to the whole socio-economic system. In this sense, IO seems a promising approach [36].

Finally, a holistic analysis of the full energy-economy-environment system in the context of the transition towards RES is needed, taking into account the interaction between declining EROI levels with other key factors such as climate change impacts, non-renewable energy resources availability or demand-management policies which go beyond the usual technological policies.

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