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Dynamic Energy Return on Energy Investment (EROI) and material requirements in scenarios of global transition to renewable energies

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ABSTRACT

A novel methodology is developed to dynamically assess the energy and material investments required over time to achieve the transition from fossil fuels to renewable energy sources in the electricity sector. The obtained results indicate that a fast transition achieving a 100% renewable electric system globally by 2060 consistent with the *Green Growth* narrative could decrease the EROI of the energy system from current ~12:1 to ~3:1 by the mid-century, stabilizing thereafter at ~5:1. These EROI levels are well below the thresholds identified in the literature required to sustain industrial complex societies. Moreover, this transition could drive a substantial re-materialization of the economy, exacerbating risk availability in the future for some minerals. Hence, the results obtained put into question the consistence and viability of the *Green Growth* narrative.

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 favourable 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 on demand. 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, 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] (see eq. (1)).

$$EROI = \frac{energy\ returned}{energy\ invested} \tag{1}$$

$$Net\ energy = energy\ returned \bullet \left(1 - \frac{1}{EROI}\right) \tag{2}$$

Hence, in the context of the forthcoming energy transition, considering the energy investments related with the construction and operation of the new RES power plants, as well as the implications on the full system, represents a number of advantages in energy system analysis in relation to the conventional approach disregarding this factor [10]:

- From a societal/metabolic point of view, the relevant dimension is the energy available to the society (*Net energy* in eq. (2)), not the energy produced by power plants (*energy returned* in eq. (2)). In fact, a favourable EROI over the long-term (energy surplus) has been associated in fields such as biology or anthropology as a key driver of increasing complexity and evolution for plants, animals and humans [11–14].
- From a technical point of view, the EROI metric includes 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.). In fact, the energy transition to new energy resources and new energy conversion and storage devices will affect the fraction of energy reinvestment, which may have significant economic impacts [10,15–21].

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Abbreviations

BAU	Business-*as*-usual
CED	Cumulated Energy Demand
CF	Capacity factor
CSP	Concentrated Solar Power
Dmnl	Dimensionless
EnU	Energy Used
EROI	Energy Return On energy Invested
EROI FC	EROI system feedback factor
ESOI	Energy Stored On energy Invested
EV	Electric Vehicle
FEI	Final Energy Invested
GCF	Grid correction factor
GDP	Gross Domestic Product
GDPpc	Gross Domestic Product per capita
GG	Green Growth
GHG	Greenhouse gas
HVDC	High-voltage Direct Current
IPCC	Intergovernmental Panel on Climate Change
LCA	Life-cycle analysis
MEDEAS-W	MEDEAS-World model
OEU	Own-energy use
OG	Overgrids
O&M	Operation and maintenance
PHS	Pumped hydro storage
PV	Photovoltaic
RCP	Representative Concentration Pathway
RES	Renewable Energy Source
SC	Self-consumption
SSP	Shared Socioeconomic Pathway
TFEC	Total Final Energy Consumption
TFEI	Total Final Energy Investment
TFES	Total Final Energy Supply
USGS	United States Geological Service
WIOD	World Input-Output Database

Glossary

Capacity factor (CF)	the ratio of the actual electrical energy output over a given period of time to the maximum possible electrical energy output over the same period.
Energy Used (EnU)	energy use throughout the life cycle of a product, including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials
Energy return on energy invested (EROI)	ratio between the energy delivered from a process divided by the energy required to get it over its lifetime.
Energy stored on energy invested (ESOI)	ratio between the energy stored in a storage device divided by the energy required to get it over its lifetime.

- Computing the EROI of each technology endogenously and dynamically makes it possible to detect potential harmful situations of increasing gross energy output while decreasing the net energy delivered to the society, i.e. the so-called “energy trap” [21–23]. The relationship of EROI to net energy is non-linear, and consequently its impact can potentially be misjudged. In extreme cases, a too low EROI, even if the gross energy consumption is increasing, may even trigger a collapse of the full system. In this sense, the net energy approach makes it possible to endogenize the concept of minimum EROI for maintaining the level of prosperity of a given society [19,24].

Much work has been carried out to estimate the EROI of individual RES technologies (e.g. Refs. [9,25–31]); 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) [27,30,32–36]. In relation to the boundaries of the analysis, different EROI categories have been defined [9] [1]:

- Standard EROI (EROIst): it includes the on-site and offsite (i.e., energy needed to make the products used on site) energy requirements to get the energy (e.g. build, operate and maintain a power plant). This EROI calculation is applied to fuel at the point where it leaves the extraction or production facility (well-head, mine mouth, farm gate, etc.). This approach allows for the comparison of different fuels even when the analysts do not agree on the rest of the methodology that should be used [37].
- Point of Use EROI (EROIpou): it includes the energy costs to get and deliver the fuel to the point of use of society (e.g. refinement, transportation, etc.).
- Extended EROI (EROIext): it considers the energy required to get, deliver and use a unit of energy, i.e. the energy required to produce the machinery and devices used to build, operate and maintain a power plant or a transportation facility (tank truck, pipeline, etc.) as well as the energy required for exploration, investment, communication, labour, etc. in the energy system.

As the boundaries of the analysis are expanded, the energy cost of getting it to that point increases, resulting in a reduced EROI (EROIst > EROIpou > EROIext). In parallel, the complexities and uncertainties to estimate each EROI category also increase by expanding the boundaries.

Thus, it is of key importance to understand both the socioeconomic and technical consequences of the large-scale replacement of fossil fuels with RES. In this sense, it is important to properly estimate the future trends in the EROI of future energy fuels, and in particular of renewable energy systems, which will be affected by factors of opposite sign: on the one hand, the EROI may increase due to technological innovation (not to confound with learning rates (e.g. Ref. [38])) or improved mineral recycling rates. On the other hand, different factors will tend to decrease the future EROI of the system, such as the need for increased back-up generation, grids and storage [8,31,39,40], the increase in energy requirements due to the ore decrease of minerals [41,42], the need to allocate increasing resources as defensive expenditures to adapt and overcome climate change impacts [43,44], etc.

The literature review reveals that recent work has been directed to estimate the historic evolution of EROI of existing national energy systems and fossil fuel extraction. A diversity of methodologies is being applied. In relation to the estimation of the historic evolution of the EROI of national energy systems, Lambert et al. [45], developed a proxy method to estimate the standard EROI of a country including all domestic and imported energy fuel sources that a nation uses, considering that there is a relation between EROI and fuel prices. The method was then applied to numerous countries, finding a wide range between 5:1 and 40:1. Brand-Correa et al. [46], estimated the evolution of the EROI

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[1] Charles Hall, the originator of the term if not the concept of EROI, believes that EROI is most properly used for the initial step of getting energy from nature. Other considerations, which are important, are matters of downstream systems efficiency. Nevertheless, he does think EROIpou is useful if well defined (Personal Communication, May 2019).

of UK developing a novel method combining physical and monetary data using Multi-Regional Input-Output data and an energy extension, finding that the EROIext of the country has declined from ~14:1 in 2000 to below 6:1 in 2012 (with an equivalent EROIst of 17:1 and 9:1, respectively). Court & Fizaine [47] applied a price-based methodology to assess the historical global EROI of fossil fuels' production finding for oil and gas it is declining since the in the 1930s–40s and for coal it is still increasing. Celi et al. [48], estimated the EROI of large oil and gas corporations from their legally-mandated estimates of CO2 released. All of these methods give broadly similar results and all indicate that at the point of production fossil energies tend to be declining but still higher than renewables [9,36,49,50].

In relation to the estimation of the EROI of the system associated to high RES penetration scenarios, Trainer [51], considering usual EROIst values by technology from the literature, estimated at 5.9:1 the EROI of the electricity system of Australia associated with the 100% renewables electricity mix proposed by Lenzen et al., [52]. Limpens & Jeanmart [53] developed a novel and more sophisticated approach in which the maximization of the EROI of the Belgian electricity system allows them to find an optimal mix of generation and storage technologies (pumped hydro storage, batteries and power to gas) with 1 h resolution. The found values for the EROI of the system range 9.7:1 ("net EROI" following their nomenclature) for a penetration of RES of 20%, and decrease to 5.4:1 for 100%. Palmer [20] developed a framework for estimating EROI of energy systems including storage options, and Barnhart et al. [15], included both storage and curtailment. The GEMBA model [54] considers a dynamic function over time of the EROI of each renewable and non-renewable resources, assuming a peaking function which is a product of two components: one technological that serves to increase energy returns as a function of production (which may serve as a proxy measure of experience), i.e. technological learning; and the other diminishing energy returns due to declining physical resource quality (for more details see Ref. [55]). The main finding of the GEMBA model is that growth of the renewable energy sector may impact investment in other areas of the economy and thereby hinder economic growth.

The aforementioned studies typically 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. This assumption holds only if the system is in "steady state", which by definition does not correspond with energy transition contexts. New power plants require upfront energy investments, providing energy returns only over the lifespan of the facility. Hence, this representation captures 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 [21,22,56–58]. Sgouridis et al. [58], build a global energy model dynamically accounting for the upfront energetic costs of solar CSP, solar PV and wind based on standard EROI values from the literature, and focused on the estimation of the optimal growth rate of these technologies to achieve system decarbonisation and providing a certain level of per capita net energy available to society. Sers and Victor [21] construct a model that includes the EROI metric (considering a decline with cumulated installed capacity) and the energy characteristics of renewable generation into a macroeconomic framework, finding that renewable investment rate has the potential to crowd out other forms of investment leading to a declining economic growth rate in scenarios of strong emissions mitigation as the ones required to avoid dangerous climate change (in accordance with GEMBA's [54] results). King and van den Bergh [59] analysed the implications in terms of net energy use of the scenarios proposed by the IEA & IRENA [60] (framed in gross energy), considering a range of EROI for energy technologies, identifying a potential "energy trap" scenario when considering EROI of technologies from the lower range of the literature. Additionally, they analysed the additional growth of solar and wind to maintain the present net energy returns, concluding that these power sources should grow two to three times faster than in other proposals not considering these energy investments.

This paper describes the methodology applied to represent the implications that the future energy investments to achieve the transition to RES may have for the full system in the simulation model MEDEAS-World (MEDEAS-W). This model is a global energy-economy-environment system dynamics model focused on the biophysical and economic dimensions and interactions arising during energy transitions [61,62]. The proposed approach includes 3 key novelties which go beyond the current state-of-the-art of the field by including:

1. Dynamic and endogenous calculation of the EROIst of each RES variable technologies for electricity generation computing the required up-front energetic costs taking as a starting point the materials required in the construction, operation, maintenance and dismantling phases and combining this data with the energy consumption per unit of material consumption from Life Cycle Analysis (LCA). For RES dispatchables, i.e., those can be used on demand, a static approach considering the EROI over the lifetime is taken.
2. Dynamic and endogenous computation of the EROIst of the whole energy system. Given that in energy systems the operating technologies are complementary and dependent, it is not possible to allocate accurately the requirements of overgrids, storages and overcapacities to any specific technology given that they are affected by different variability patterns [51]. Hence, it is not totally correct to estimate the EROI of full energy systems by using estimates of "buffered" EROIs for each individual renewable technology (as done for example by Refs [3,27,31] including works from some authors of this paper, although this approach may be useful for other purposes such as identification of the implications for intermittency management that these technologies introduce in the system). 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.
3. Incorporation of the implications of the variations in the EROI of the system for the whole system due to the use of an energy-economy-environment model with interlinks between different dimensions allowing to account for the net energy actually available for the society.

This work focuses both on energy and material requirements associated to the transition to RES. First, the lower power density of renewable energies with relation to fossil fuels translates into a substantially higher (in quantity and diversity) material demand intensity to build the structures for harnessing the renewable energy flows from the biosphere [3,63–67]. Second, there is a tight link between both, given that energy is required to extract, process and concentrate materials; and materials are required to construct the energy generation and transportation facilities. Although metal recycling and technological change may contribute to future supply, mining is generally expected to continue growing for the foreseeable future to ensure demand fulfilment in an expanding economic system [68,69]. Hence, the endogenization of the EROI of the individual technologies in MEDEAS-W requires data on the actual material intensity (kg/MW) of these technologies. 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 [70,71]. 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. Requirements for a total of 58 materials, of which 19 are minerals, have been reviewed. This way, the model allows to compute the mineral requirements related with the expansion of alternative energy technologies. This assessment is of great importance given recent works highlighting the dependence of the current economic system and alternative technologies on minerals [64–67,72–75]. In particular, García-Olivares et al. [74], proposed a global alternative mix to fossil fuels based on proven RES technologies, power transport and for some future transport systems not relying on scarce materials. They found that the proposed alternative would still be strongly constrained by the availability of metals such as lithium, nickel, zinc and platinum; requiring 60–70% of the copper reserves. Valero et al. [64], analysed potential bottlenecks for 31 raw materials in the 2016–2050 time period under a business as usual scenario for wind power, solar photovoltaic, solar CSP and passenger electric vehicles, identifying 13 elements having very high or high risk: cadmium, chromium, cobalt, copper, gallium, indium, lithium, manganese, nickel, silver, tellurium, tin and zinc. Although this work is focused on the implications of the energy transition on the EROI of the system, it also contributes to this emerging research topic highlighting the vulnerability due to the potential scarcity of some minerals.

The importance of dynamic and endogenously computing the energy and material investments is illustrated by the simulation within the integrated assessment model MEDEAS-W of three scenarios with different targets of penetration of renewables in the electricity mix to 2060 under a *Green Growth* narrative (GG), which is an alternative paradigm frequently assumed to avoid the adverse impacts on human societies of the global environmental change [76–81].

The remaining of the paper is structured as follows: section 2 describes the applied methodology to integrate the material and energy investments related with renewable for electricity generation in MEDEAS framework; section 3 describes the scenarios applied and section 4 reports and discusses the obtained results. Section 5 concludes.

2. Methodology

MEDEAS dynamically computes the EROI[2] of the full energy system and its feedback to the energy demand, acknowledging that the system boundary also varies along the temporal dimension [22,37,56]. The EROI of the system is estimated using information from literature review and LCA to dynamically account for the up-front costs of the energy investments and the delayed return of energy generation for the renewable technologies for electricity generation (taking as starting point the level of materials required in the construction, operation, maintenance and dismantling phases), and assuming constant the EROI of the rest of fuels (non-renewables and non-electric RES).

Section 2.1 documents the methodology to compute the EROIst of the system, section 2.2 documents the dynamic expression of EROIst applied, together with the specification of factors required for its calculation. Section 2.3 is focused on the methodology to feedback the EROI variation into the rest of the MEDEAS-W model, which is overviewed in Appendix A.

2.1. EROI of the energy system

Fig. 1 represents the energy metabolism of our society with different energy flows and conversions, from primary sources to the energy delivered to society. Each arrow from Fig. 1 represents:

(0) Primary sources of energy available to society
(1) Useful energy used by society
(2) On-site and offsite (i.e., 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 properly manages RES intermittency
(4) Energy used for the distribution of energy
(5) Energy requirements to build the machines and infrastructure required to construct the machines and infrastructure which allows to make the energy investments (2), (3) and (4) (i.e., indirect energy costs [36,37,46,47]).

The dynamic EROIst of the system is defined in this work following eq. (2) of Murphy et al. [37], as the ratio between the final energy delivered to society and two factors: the energy requirements to build, operate, maintain and dispose the plant of energy generation; and the energy requirements so the system properly manages RES intermittency ($EROI^{st}_{system}$, eq. (3)). Our dynamic approach shortens the time step of the calculations significantly (in the order of months), with relation to conventional EROI studies, where the lifetime of the technology is the usual operational unit of the analysis:

$$EROI^{st}_{system} = \frac{(1)}{(2) + (3)} \tag{3}$$

Note that for an individual technology, its EROIst is usually defined in the literature as (1)/(2) (e.g. Refs. [27,35]).

If extending the boundaries, i.e., including more factors such as the energy required for the distribution of the final energy to the point of use, the EROI of the system from a "point of use" approach ($EROI^{pou}_{system}$, eq. (4)) can be defined as follows:

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

A step further would be to account for the total energy requirements (5, see Fig. 1) to make the energy investments (2), (3) and (4). This way we would arrive to an "extended" definition of the EROI of the system:

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

The resulting net energy available (pou) to society can be obtained as shown in eq. (6):

$$Net\ Energy_{pou} = (1) - (2 + 3 + 4)) \tag{6}$$

Discretionary uses of the energy, i.e., the uses of energy not related with the energy system, are:

$$\begin{aligned} Discretionary\ energy\ uses &= Net\ energy_{pou} - (5) \\ &= (1) - [(2) + (3) + (4) + (5)] \end{aligned} \tag{7}$$

To be viable, any system requires that Net Energy > 0. Additionally, any complex system requires that discretionary energy uses > 0 in order to allow for the system to have energy available for other uses than self-maintaining the system.

What are the implications of different EROI of the system levels for the net energy and discretionary uses delivered to society? Fig. 2 represents at scale the energy flows to deliver the same net energy to society associated to a "high" (EROIpou = 10:1) and "low" (EROIpou = 2.5:1) EROIpou of the system, respectively. At "high" EROI system levels, the energy investments for delivering energy to the consumers are relatively small, and there is not a large difference between final and net energy delivered to society. However, maintaining the same level of net energy delivered to society at "low" EROI system levels, the energy investments have reached such a relative size that the primary energy supply has to increase substantially (hence increasing the associated environmental impacts), even if the losses decrease. In

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[2] Note that dynamically accounting for energy magnitudes corresponds with power rather than energy. Despite our dynamic approach significantly shortens the time step of the calculations (in the order of months), it represents still an average power over a certain time (which in conventional EROI studies corresponds with the lifetime of the technology). Hence, we decided to avoid the creation of a new term given that EROI is a concept widely used, and follow the terminology from Refs. [22,56] of "dynamic EROI" (although other works have coined terms such as "net external power ratio" (NEPR) [82]).

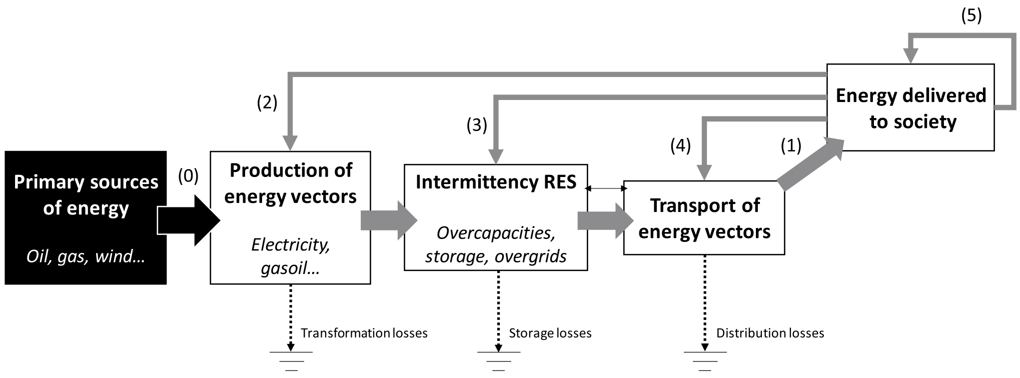

Fig. 1. Representation of the energetic metabolism of our society. Grey arrows refer to energy flows that are useable by human societies. The black arrow on the left-hand side (0) is a flux of materials with potential energy which can be transformed into useable energy. Dashed vertical arrows represent energy losses at each phase of the chain (transformation, storage and distribution losses). An exosomatic intermediary (arrows 2, 3, 4 and 5 representing energy investments) is always required to transform the potential energy into useful exosomatic energy useable by the society (1) (excluding non-energy uses). White colour refers to the anthroposphere and black colour to the biosphere which encompasses it. The thin arrow between "Intermittency RES" and "Transport of energy vectors" represents the fact that the electricity transmission and distribution losses are dependent on the share of RES in the electricity mix. (Size of arrows is not to scale).

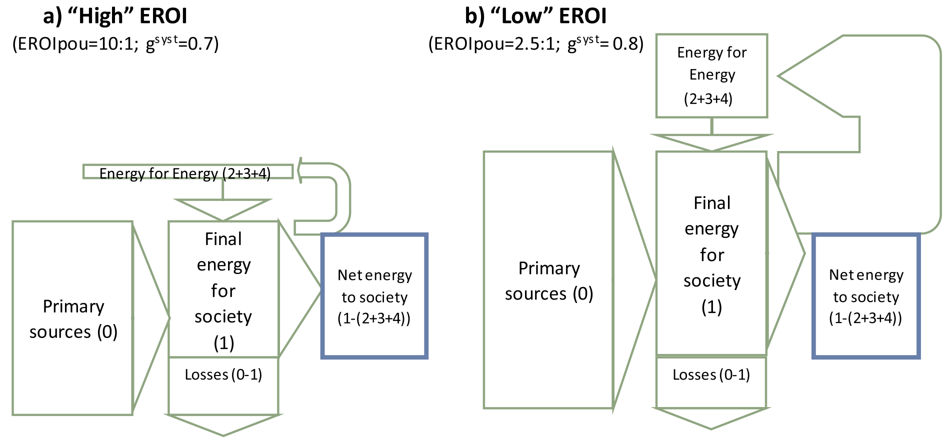

Fig. 2. Representation at scale (vertically) of the energy flows associated to the same level of net energy delivered to the society in the case of: (a) "High" EROI (EROIpou = 10 and g^{syst} = 0.7); and (b) "Low" EROI (EROIpou = 2.5 and g^{syst} = 0.8). Numbers refer to nomenclature in Fig. 1.

the case of accounting for (5), the discretionary energy uses for society would be even smaller.

As aforementioned, 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 monetary costs to energy inputs (e.g. Refs. [30,32]). This methodology and their results are disputed by other authors given the uncertainties in these calculations [35,83]. The EROIpou of the system also faces methodological challenges given the difficulties to consistently estimate the energy investments associated with the transportation of energy vectors, such as pipelines, electric grids, fuels for tank trucks, oil tankers and gas tankers, but also the share attributable to energy distribution of energy investments to build and maintain roads, railways and other transportation methods which have double uses [19]. Acknowledging the difficulties to compute the EROIext based solely in physical terms (i.e. avoiding the controversy of the energy intensities methodology) as well as the EROIpou, a first step, conservative approach, is taken in this work estimating the EROI of the system from a standard ($EROI^{st}_{system}$) approach.

The following assumptions are taken to compute the $EROI^{st}_{system}$ in this work:

- The EROIst of non-renewable energy sources (oil, gas, coal and uranium) is assumed to be constant over time. Given that in the long term the EROI of these fuels will tend to decrease due to geological depletion (as recent analyses are pointing out that it is already the case for fuels such as oil and gas, trends exacerbated by the growing exploitation share of unconventional fuels characterized by lower EROI [9,49,50]), this simplification can be considered as conservative.
- The EROIst is dynamically estimated for renewable technologies for the generation of electricity (see section 2.2). The EROIst of other renewables such as liquid biofuels or technologies for heat generation is considered to be constant over time.
- Option of allocation of technologies based on their relative EROIst buffered with energy investments to manage intermittency (RES technologies with a higher EROI tend to cover a larger share of the energy demand) (see Supplementary Online Material).
- Overcapacities and overgrids[3] related to the increasing penetration of variable renewable technologies in the system are endogenously computed in the model (see Supplementary Online Material). Overcapacities reduce the effective capacity factor of each technology (CF, i.e., the ratio of the actual electrical energy output over a given period of time to the maximum possible electrical energy output over the same amount of time), which also reduces its EROI. The demand of materials for overgrids (high power and HVDC) is

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[3] Overgrids related to the increasing penetration of variable renewable technologies would more precisely correspond to the concept of EROIpou. However, given that most of energy investments associated with the EROIpou are missing in this work, the nomenclature of EROIst of the system is kept. Moreover, sensitivity analysis shows that overgrids contribution to the EROI is substantially lower than other components (see section 4 on Results).

modelled as an additional component of the material intensity (kg/MW) of the construction of new capacity for each RES variable technology (as described in section 2.4.4.1 in Capellán-Pérez et al. [61]).

- Additional losses due to storage use are modelled following Barnhart et al., [15]. 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)); the stored fraction (ϕ) energy that would have been curtailed without storage and the efficiency of the electric storage (η). The following eq. (8) represents the EROIst at grid scale for a given RES variable technology i.

$$EROIst_i^{grid} = \frac{1 - \phi_i + \phi_i \eta_c}{\frac{1}{EROIst_i} + \frac{\phi_i \eta_c}{ESOI_c}} \tag{8}$$

η_c represents the combined storage efficiency of PHS and EV batteries and $ESOI_c$ represents the combined energy stored on electrical energy invested of PHS and EV batteries. ϕ is fixed at 20% for the sake of simplicity[4].

Points 1 and 2 are modelled assuming that the ratio of energy industry own-energy use in relation to the total final energy consumption (excluding non-energy uses and the electricity generated by renewable technologies) is constant over time (data from IEA Balances [84]).

Summarizing, MEDEAS dynamically accounts for the EROIst of the system (dimensionless units) as follows (eq. (9)):

$$EROI\,(t)_{system}^{st} = \frac{TFEC\,(t)}{g^{syst}\,(t) \bullet (OEU\,(t) + TFEI\,(t)_{RES\ elec} + TFEI\,(t)_{storage\ elec})} \tag{9}$$

TFEC: total final energy consumption (excluding energy materials for non-energy uses).

$TFEI_{RES\ elec}$: total final energy investments for renewable technologies of electricity generation (construction, replacements, operation and maintenance, decommissioning and overgrids).

$TFEI_{storage\ elec}$: total final energy investments for storage of electricity.

OEU: Energy industry own energy use. For the historic period, it corresponds with the TOTENGY[5] category in the IEA World Energy Balances [84], of the total final energy consumption excepting the electricity generated by renewable technologies to avoid double accounting. For projections, the ratio between OEU and TFEC (excepting the electricity generated by renewable technologies) for the year 2015 is maintained into the future (10.5%).

g^{syst}: final to primary energy ratio (1)/(0) (see Fig. 1). Different authors use different criteria for the value of g depending on the assumption about the quality of the electricity in relation to the rest of the energy consumed [27,30,31,40]. However, all values considered are static. Given that we are projecting the evolution of the EROI in changing energy mix, an alternative approach had to be developed. Since we start for the calculation of the EROI from the final energy (1) (see eq. (3)) and the electricity is not the only final form of energy in the system, it is inferred that to give the same energy services to the society, less final energy (1) will be required as the system evolves towards sources of greater exergy (e. g. the share of electricity in the full energy mix increases). To be able then to compare between evolving energy systems, we follow the approach developed by de Castro and Capellán-Pérez [27] and compute $g^{syst}(t)$ as the dynamic ratio between the total final energy consumption and the total primary energy supply (excluding the energy dedicated to non-energy uses) in the whole system. Hence, the dynamic implementation in a full energy model allows to endogenize the g^{syst} factor dynamically, given that the transformation of primary energy to final energy will change during the transition to renewables. $g^{techn} = 1$ is defined for the computation of the EROI of each of the renewable technologies for the generation of electricity (see section 2.2).

See Appendix A for an overview of the modelling framework of MEDEAS.

2.2. *Modelling of the dynamic EROIst of RES technologies for electricity generation*

The construction of power plants requires a large upfront energy investment, providing energy returns only over the lifespan of the facility partially compensated by the energy requirements of the operation and maintenance (O&M) activities, which is ultimately followed by another phase of energy investment for decommissioning of the facility. In cases where the information about the energy required in each phase is available, a dynamic approach can be applied for the estimation of the EROI of the technology [22,56,58]. Otherwise, a static approach assuming that the energy invested is proportional to the energy obtained along the lifespan of the functioning power plant has to be adopted.

Given the difficulty and time-intensiveness to estimate the energy and material requirements for all the alternative energy technologies, a selection was performed. This way, the scalable RES for electricity generation were selected (solar PV, solar CSP, wind onshore, wind offshore; note that these are variable intermittent RES), as well as the electric storage and overgrids requirements. The energy requirements for the construction of the rest of RES technologies for electricity generation (which correspond to the dispatchable technologies: hydroelectricity,[6] geothermal, biomass&waste and oceanic[7]) as well as other storage systems such as pumped hydro storage were also included but in a simplified (static) manner. For the sake of simplicity, all the estimates considered have been derived from physical inputs excluding indirect estimates based on associated economic costs.

To estimate the EROI of RES technologies for electricity generation we apply the classic definition of standard EROI [9] assuming $g^{techn} = 1$. Eq. (10) shows the EROI (dimensionless units) for a given energy supply infrastructure of technology i over its whole lifetime (L) defined from a "static" perspective. Eq. (11) shows the expression of the annual electricity output:

$$\begin{aligned} EROI_i &= \frac{Annual\ elec\ output_i \bullet (1 - GCF) \bullet L_i}{\left(EnU_i^{New\ cap+OG} + EnU_i^{Decom\ wear\ cap} + EnU_i^{O\,\&\,M} \bullet L_i\right) \bullet g^{techn} + Annual\ elec\ output_i \bullet L_i \bullet SC_i} \\ &= \frac{Annual\ elec\ output_i \bullet (1 - GCF) \bullet L_i}{\left(EnU_i^{New\ cap+OG} \bullet (1 + Decomm) + EnU_i^{O\,\&\,M} \bullet L_i\right) \bullet g^{techn} + Annual\ elec\ output_i \bullet L_i \bullet SC_i} \end{aligned} \tag{10}$$

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[4] This factor is exogenously set ad hoc to 0.2 in all simulations. Sensitivity analysis showed that results are not sensitive to this factor. Sgouridis et al. [58], consider a similar (ad hoc) value of 10% for this parameter.

[5] TOTENGY covers the amount of fuels used by the energy producing industries (e.g. for heating, lighting and operation of all equipment used in the extraction process, for traction and for distribution).

[6] The intermittence and seasonal variability of the rains, as well as the requirements of other water resources such as irrigation, may limit the capacity of hydroelectric energy to be considered as 100% dispatchable. This limitation has not been considered.

[7] A great diversity of marine technologies exists and some of them could be considered as dispatchable (e.g. OTEC) while others are subject to variability (e.g. tidal & wave). For example, the wave plant of Mutriku (Spain) presents a factor of almost 5 in its seasonal variability comparing summer and winter [85]. For the sake of simplicity and thus from a conservative point of view, we assume that all oceanic power is dispatchable. Moreover its importance in the model is reduced given its low potential and EROI (see Ref. [61]).

$$Annual\ elec\ output_i = CF_i \bullet Installed\ new\ cap_i \bullet 8760 \frac{h}{yr} \tag{11}$$

i: electricity generation technology.
Annual elec output: Annual electricity output.
CF: capacity factor.
Installed new cap: installed new capacity.
L: lifetime of the installed infrastructure.
$EnU^{New\ cap+OG}$: energy used in the construction of new capacity and overgrids for RES variables (EnU in this work corresponds to “Cumulative Energy Demand” (CED) in most EROI-related literature, see section 2.2.2.2 for clarification).
$EnU^{Decom\ wear\ cap}$: energy used for decommissioning those infrastructures that have ended their lifetime. We assume a fixed share in relation to the EnU of the energy required for the construction of each power plant of 10% following Hertwich et al., [86], i.e. Decomm = 0.1.
GCF: Annual losses due to the Joule heating within each power plant (grid-correction factor) as a share of total annual electricity output. This is endogenously calculated by the model as distribution and transmission losses (see Supplementary Online Material).
$EnU^{O\&M}$: annual energy used for the operation and maintenance.
SC: electricity self-consumption of the power plant as a share of the electricity output.

Eq. (11) can be simplified removing the annual installed electricity capacity and expressing the EnU as energy per installed capacity (eq. (12)):

$$EROI_i = = \frac{CF_i \bullet (1 - GCF) \bullet 8760 \frac{h}{yr} \bullet L_i}{(EnU_i^{New\ cap+OG} per\ TW \bullet (1 + Decomm) + EnU_i^{O\&M} per\ TW \bullet L_i) \bullet g^{techn} + CF_i \bullet 8760 \frac{h}{yr} \bullet L_i \bullet SC_i} \tag{12}$$

2.2.1. *Static expression of EROIst for RES dispatchable technologies*

Eq. (12) can be directly applied for those technologies of electricity generation for which the material requirements for both new installed capacities and O&M are explicitly modelled since MEDEAS dynamically estimates their $EnU^{New\ cap+OG}$ and $EnU^{O\&M}$ (see section 2.2.2). However, given that these data are not available for the dispatchable technologies, the static approach of EROI has to be applied instead for hydroelectricity, geothermal, biomass&waste and oceanic.

For this, some assumptions have to be made in order to adapt eq. (10) (in combination with eq. (11)): that the O&M are independent of the CF and the self-consumption losses are negligible. The current total EnU per capacity (EJ/TW) for each technology i over the lifetime of the infrastructure is then (eq. (13)):

$$Total\ EnU_i\ per\ TW\ over\ lifetime = \frac{CF_i^{initial} \bullet L_i \bullet 8760 \frac{h}{yr} \bullet EJ\ per\ TWh}{EROI_i^{initial} \bullet g^{techn}} \tag{13}$$

$CF^{initial}$ refers to the initial (current) capacity factor for each technology (without accounting for eventual decreases due to overcapacities).

$EROI^{initial}$ is the initial (current) EROI level associated to the initial (current) capacity factor. This EROI level is conservatively considered constant[8] (see Table 1).

Thus, once estimated the current total EnU per TW for each technology, and assuming that its value will remain constant during the timeframe of MEDEAS, the evolution of EROI over time of the dispatchable electricity generation sources can be expressed by eq. (14). Note that, despite being defined following a “static” approach, the EROI can still evolve over time considering the evolution over time of the capacity factor of each technology $CF_i(t)$ (which depends on the level of overcapacity, see Supplementary Online Material):

Table 1
Assumed EROIst levels over lifetime for each of the RES dispatchable technologies for electricity generation.

Technology	EROIst (static definition)	Reference
Hydroelectricity	50:1	[89]
Geothermal	7:1	[61]
Biomass	1.5:1	[26]
Oceanic	3.25:1	[61]

$$EROI_i(t) = \frac{CF_i(t) \bullet L_i \bullet 8760 \frac{h}{yr} \bullet EJ\ per\ TWh}{Total\ EnU_i\ per\ TW\ over\ lifetime \bullet g^{techn}} \tag{14}$$

2.2.2. *Dynamic expression of EROIst for RES variable technologies*

Eq. (12) can be directly applied for those technologies of electricity generation for which the material requirements for both new installed capacities and O&M are explicitly modelled since MEDEAS dynamically estimates their $EnU^{New\ cap+OG}$ and $EnU^{O\&M}$ (see section 2.2.2). Fig. 3 shows the conceptual representation of the energy inputs and output for power plants for variable renewable electricity generation considered in MEDEAS framework which correspond with the RES variables: solar PV, solar CSP, wind onshore and wind offshore.

Hence, the EROI for these technologies the EROI can be endogenously and dynamically estimated in the model for each time period t (i.e. independently of the lifetime of the infrastructure), see eq. (15):

$$EROI_i(t) = \frac{Annual\ elec\ output_i(t) \bullet (1 - GCF(t)) \bullet EJ\ per\ TWh}{(EnU_i^{New\ cap+OG}(t) + EnU_i^{decom\ wear\ cap}(t) + EnU_i^{O\&M}(t)) \bullet g^{techn} + Annual\ elec\ output_i(t) \bullet SC_i} \tag{15}$$

$EnU^{New\ cap+OG}(t)$ and $EnU_{O\&M}(t)$ depend on the recycling rates of the minerals.

$EnU^{decom\ wear\ cap}$: assuming that the energy used for decommissioning electricity plants is 10% of the energy required for its construction [86], the dynamic expression of the EnU for decommissioning power plants would thus be:

$$EnU_i^{decom\ wear\ cap}(t) = 10\% \bullet EnU_i^{New\ cap+OG}(t) \bullet \frac{wear\ cap_i(t)}{Installed\ new\ cap_i(t)} \bullet \tag{16}$$

2.2.2.1. *Demand of materials for each technology*

The demand of materials in MEDEAS-W is split in 2 categories: (1) materials demanded by alternative technologies for the energy transition (which is the focus of this section), and (2) materials demanded by the rest of the economy (see Appendix B.1).

A literature review was performed in order to identify the material intensity (kg/MW) required by the key modelled technologies for the transition towards fully RES-based energy systems: solar PV, solar CSP, wind onshore, wind offshore, electric vehicle batteries and electric grids. For the electricity generation technologies, both new installed capacity and O&M activities are considered.

We reviewed a total of 58 materials, of which 19 minerals (aluminium, cadmium, chromium, copper, gallium, indium, iron/steel, lead, lithium, magnesium, manganese, molybdenum, nickel, silver, tellurium, tin, titanium, vanadium and zinc). Selection criteria was made

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[8] In fact, there is a relationship between cumulative use and EROI of RES (e.g. Ref. [87]). For hydro, some empirical evidence suggests that the global EROI of hydro may also be declining [88].

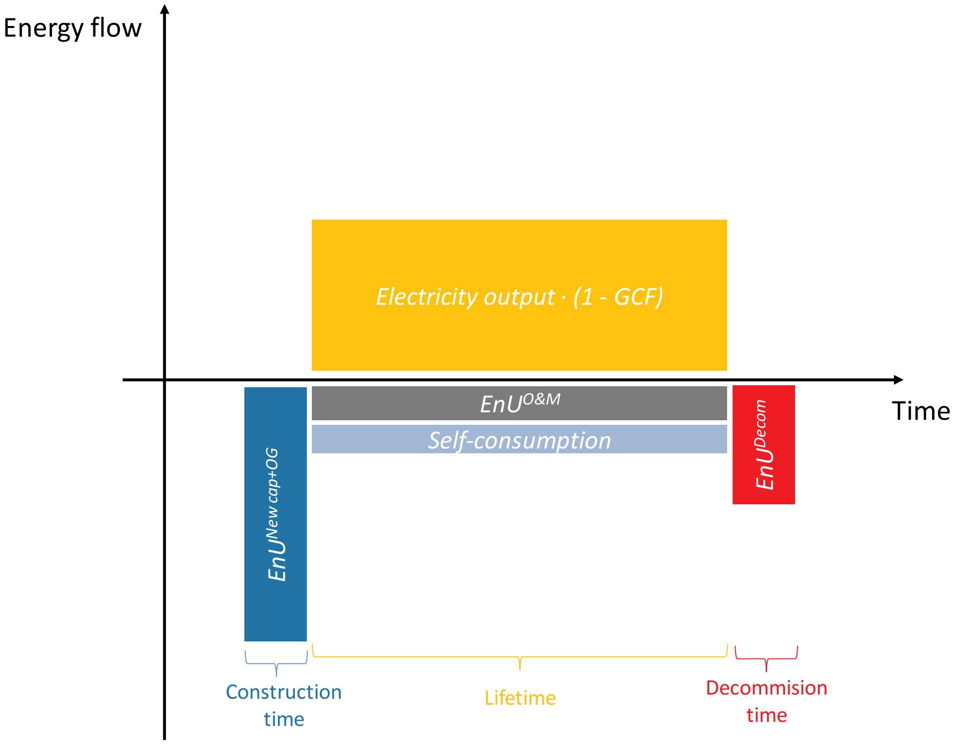

Fig. 3. Conceptual representation of the energy inputs and output for power plants for variable renewable electricity generation considered in MEDEAS framework (see eq. (15) and adapted from Murphy et al. [37], not to scale).

Table 2
Representative alternative technologies and main references considered for their material intensities. See Supplementary Material for details.

Alternative technology	Representative technology	Main references for material intensities
Solar CSP	CSP with molten-salt storage without back-up: most efficient and used technology [27]. Back-up option is not considered since it is usually powered by non-renewable fuels such as natural gas.	[27,61]
Solar PV	Fixed-tilt silicon PV: better performance in terms of EnU and EROI [30] and subject to less mineral availability constraints [93] although current share of thin-film technologies in global PV mix is considered.	[27,30,61,89,94–96]
Onshore wind	2 MW onshore wind turbines: currently the global average wind onshore installed capacity per turbine is ~1.4 MW [97].	[61,98]
Offshore wind	3.6 MW offshore wind turbines taking as reference the current average size in Europe [97]	[61,98–100]
Electric vehicle battery	$LiMn_2O_4$ electric vehicle batteries: although they are less efficient than other alternatives (e.g. $LiCoO_2$), the embodied energy for their fabrication is substantially lower [101].	[61,102–104]

on the basis of considering all relevant materials to accurately estimate the embodied energy for the EROI estimation, as well as potential critical materials identified in the literature (e.g. Refs. [64,72–75]), as well as on specific assessments (see Ref. [61]). A comprehensive literature review was performed in order to collate the most robust and accurate data about material requirements for each technology. This approach differs from published meta-analyses which tend to focus on the average values of the range of parameters found in the literature [9,25,28,51,90]. In the cases where published data for an element/phase of the manufacture/installation of the technology was not found, the material requirements have conservatively been estimated from available data from other technologies (instead of being assumed 0 as most commonly performed in the literature). For example, since no data about the material requirements for fences for CSP power plants were found, the data estimated by Prieto and Hall [30] for fences for PV were used; similarly, since no data about land clearing for PV were found, so data for land clearing for CSP was applied instead [27,91], etc. In relation to the electric grids, the additional requirement of grids (i.e. "overgrids") were estimated considering that the RES reach a high penetration in the electric mix, the losses due to Joule heating and the maintenance of grids. For the sake of simplicity, no energy inputs were derived from monetary costs, and in the case of uncertainty about potential double accounting, material requirements were not included. Hence, our estimations can be considered underestimates of the EROI of each technology.

A "representative" technology was selected for each alternative technology on the basis of their current and future expected performance. Table 2 shows the selected representative technologies as well as the main references considered in this work for their material intensities. Supplementary Material collates the material intensity for each technology for the 5 most energy intensive inputs (for more details see section 2.4.1.1 and Table 27 in Ref. [61]). Modelled mineral recycling rates correspond to the share of recycled content (RC) in the fabricated metal, current levels being taken from Ref. [92] (see Supplementary Online Material). The impact of recycling on primary production is assumed as one-to one displacement for the sake of simplicity, however in reality reprocessing generally entails material and quality losses.

2.2.2.2. Energy used (EnU). The energy used (EnU)[9] for the construction of new capacity, overgrids and O&M activities (O&M) for each RES variable technology for which the material requirements are explicitly modelled (solar PV, solar CSP, wind onshore, wind offshore) is estimated for virgin and recycled materials from an open LCA database [105] data not available were conservatively estimated, e.g., assuming the same energy requirements per unit of material consumption for by-products than for the main mineral (e.g. Ga and Te). This part of their EnU is estimated multiplying the material intensity of each technology (assumed constant) by the energy consumption per unit of material consumption (MJ per kg, average between virgin and secondary materials considering current recycling rates), whose current values constitute a starting point for the dynamic analysis. Data are cradle to gate or at most to point of use (most data are from Hammond and Jones [105], for the rest see Table 29 in Ref. [61]). Supplementary Material collates the EnU for the 5 most energy intensive inputs for the construction phase of each technology; these 5 inputs explain > 85% of the total EnU for all considered technologies. The change of recycling rates makes them evolve dynamically. Thus, the EnU of each technology i evolves endogenously for each material j (eq. (17)):

$$EnU_i(t) = Material\ intensity_i^j \left[\frac{kg}{MW}\right] \cdot Energy\ consumption\ per\ unit\ of\ material\ consumption^j \left[\frac{MJ}{kg}\right](t) \tag{17}$$

For the sake of simplicity, it was decided not to model the increase in energy requirements due to ore grade decrease of minerals in this analysis, although we acknowledge this effect may be important for some minerals in the future [41,42,106].

2.3. Modelling of the feedback of the variation of the EROI of the system

The variation of the EROI of the system implies a variation in the energy intensity of the economic sectors linked to the generation, transformation and transport of energy. This feedback effect between the energy system and the economic system has also been modelled in MEDEAS-W, but it has been necessary to do so indirectly, due to the grouping of economic sectors used in WIOD [108] (see Refs. [61,107] for a full description of the Economy module of MEDEAS).

Our adopted solution to model the change of the EROI of the system has been to consider it as an additional effect on the total final energy required and consumed by the system in relation to a reference year (2015). This way, a decrease (increase) of the EROI of the system in relation to the reference year will induce an increase (decrease) of the demand of total final energy. The application of this approach assures that the final net energy initially demanded is maintained after accounting for the EROI of the system dynamic feedback. We judge that the potential double accounting due to the combination in this work of the LCA of renewable energy technologies with national accounts (WIOD input-output tables) is more than compensated by using the EROIst metric instead of EROIpou or EROIext.

After some reworking of equations (see Supplementary Online Material), and assuming that the total energy returned (flow (1) in section 2) corresponds to $E_{inv} + N_{eds}$ (being E_{ing} the energy invested to supply N_{eds}), we obtain the EROI feedback factor (EROI FC), which corresponds to the additional effect on the total final energy required by the system in relation to the reference year ($t_0 = 2015$) to satisfy the same level of net energy as if the EROI of the system would have not changed (eq. (18)):

$$EROI\ FC(t) = \left(\frac{EROI(t)}{EROI(t) - 1}\right) \cdot \left(\frac{EROI(t_0) - 1}{EROI(t_0)}\right) \tag{18}$$

Eq. (19) shows the resulting demand by final fuel k accounting for the variation of EROI of the system and over the original demand D^0:

$$D_k(t) = D_k^0(t) \cdot EROI\ FC(t) \tag{19}$$

Hence, if EROI FC > 1, there would be an overdemand w.r.t. the initially final energy demanded, and the contrary would hold if EROI FC < 1.

3. Scenarios

We simulated three scenarios with different penetration of renewables in the electricity mix in MEDEAS-W model to 2060 under a *Green Growth* narrative (GG), which is the alternative paradigm assumed by the establishment to avoid the adverse impacts on human societies of the global environmental change [76–81]. The GG narrative focuses on successfully combining economic growth with the increase in environmental protection by achieving an absolute decoupling between economic activities increase and the consumption of energy and materials through a diversity of measures, such as a substantial increase in efficiency improvements, the electrification of the system, the transformation of the transportation sector and the rapid transition to low-carbon energy sources (renewables, nuclear and not discarding future technologies such as advanced biofuels and bioenergy combined with carbon capture and storage). These goals are expected to be achieved with a so-called 'inclusive economic growth'. The more or less explicit objective is to undertake a global modernisation process widely based on the path previously followed by developed countries, but including a technology-based transition to RES and large efficiency improvements [109–112]. In this scenario, we progressively activate policies in the period 2020–2025, which given current time (June 2019) it may be considered as an optimistic assumption.

RES currently contribute over 20% of the electricity generation at global level, with hydro dominating the renewable mix with > 70% of the global RES electrical generation. Three scenarios based on the GG narrative are simulated considering different growth rates of the RES technologies for electricity generation:

- *GG-50%*: ~50% of RES in electricity mix in 2060,
- *GG-75%*: ~75% of RES in electricity mix in 2060,
- *GG-100%*: ~100% of RES in electricity mix in 2060.

The targets are approximated given that MEDEAS-W is a simulation model. These scenarios allow us to assess the implications of RES increasing contribution in the electricity system for the whole system. For the sake of simplicity, in this work, the EROI-based allocation method of renewable energy technologies is not activated.

The quantification of the GG storyline applied in this work has been performed on the basis of a detailed literature review of scientific papers and reports from international institutions, as well as on our assessment. In general, a business-*as*-usual (BAU) scenario (a narrative which broadly assumes the extrapolation of current trends into the future) is required as an implicit reference, given that the GG narrative is built on alternative assumptions such as a higher Gross Domestic Product per capita (GDPpc) increase and a lower population growth due to higher education levels in this scenario. In particular, data from the Shared Socioeconomic Pathways (SSPs) quantifications' are considered for population (SSP1) and GDPpc (SSP2) evolution ([111,113,114]), a more equitable share of income, as well as an economic structure which

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[9] CED is a term with origin in the LCA community, where it is defined including all the primary energy harvested in the operation phase. However, this definition is not valid to calculate EROI or the Energy Payback time. To avoid confusion of the different "CEDs" being used in the literature, and given priority to the historical precedence to the CED defined by LCA community, we apply in this paper the term Energy Used (EnU) instead of Cumulative Energy Demand (CED) (the same criteria was applied in past works such as [27]).

tends towards a modern economy such as Denmark (see Ref. [107] for details on the method for its implementation). GG also assumes efficiency improvements 2x faster than historical trends both at productive sectors and households, a global afforestation program based on [115] as well as a very high increase in recycling rates (RC) of minerals assumed to reach 85% by 2060 in line with other works in the literature [116–118] (same target for alternative technologies and the rest of the economy). The role of nuclear energy in a global GG scenario is challenged by the fact that different countries and organizations/institutions have a different view. In this work, given the challenges that the nuclear industry faces [119], a slight increase in nuclear capacity is considered in accordance with the most optimistic prospects of alternative scenarios published by the IEA [110]. Different views also exist on the role of biofuels in a GG scenario. Similarly as for nuclear, for the sake of simplicity in this paper we take as reference the alternative IEA ETP scenarios [110], which assume a slow growth (half of historical trends) for conventional biofuels on cropland given their environmental impacts in parallel with a significant contribution of advanced biofuels in the future. For the renewables dedicated to heat generation we assume a doubling of the annual historic short-term averaged growth rates of installed capacity (with a maximum of +20%/year to avoid unrealistically high growth rates). With relation to inland and households transport, a transition towards electric and hybrid vehicles is assumed in light vehicles and public transportation, however for the case of heavy vehicles and air and water transport, we consider there will not be a substantial replacement of conventional fuels by electric alternatives given the involved technological challenges which remain unresolved [61,120–122].

Table 3 shows the most relevant variables and hypotheses set in MEDEAS-W for simulating the GG scenario in this work.

4. Results and discussion

This section reports and discusses the results obtained with MEDEAS-W under the scenarios described in section 3. Section 4.1 focuses on the energy investments associated to the transition to RES, including the resulting EROI of the system, its systemic implications and a comparison with the literature. Section 4.2 reports the main results in relation to the material requirements associated to the transition to alternative technologies.

4.1. Energy investments

4.1.1. Transition to RES and dynamic EROI of the system

Fig. 4 shows the dynamic evolution for the three scenarios considered in this work of the EROIst of the variable RES technologies for electricity generation whose EROI has been dynamically modelled: wind onshore, wind offshore, solar PV and solar CSP (see section 2.2.2).

Table 3

Overview of the most relevant scenarios inputs for simulating the *Green Growth* (GG) scenario.

Scenario inputs & assumptions	*Green Growth* (GG)	Reference
Desired GDPpc growth (2015-2060 yearly average)	Historical trends (1979–2014): +1.4%/yr	
Population growth (2015-2060 yearly average)	SSP1 (+0.4%/year)	[112,114]
Target labour share (2050)	60 %	[108]
Target A matrix (2060)	2009 Denmark IOT	[108]
Phase-out oil for electricity and heat?	Linear phase-out from current share to 0 by 2030.	Own estimation
Efficiency improvements (Final energy intensity)	2x times increase historical efficiency improvement trends by sector/households and fuel	Own estimation
Inland and households transport		Own estimations from [63,121,122].
Electric vehicles&hybrid shares target per category in 2060:		
4-wheel vehicles (including light cargo)	70%	
2-wheel vehicles	50%	
Heavy vehicles	20%	
Bus	70%	
Global afforestation program?	Yes	[116]
Nuclear installed capacity	Moderate capacity increase (+2.5%/year)	High range from literature review [111]
Recycling rates of minerals (19 minerals)	Target of 85% recycling rate (RC) by 2060 for all minerals	[117–119]. Current recycling rates (RC) from [93].
Renewables		
Annual capacity growth of RES for electricity		Potential [63]
Hydroelectric	*Scenario-dependent*	31.5 EJ/yr
Geothermal	*Scenario-dependent*	9.5 EJ/yr
Bioenergy	*Scenario-dependent*	Shared potential for heat, liquids and electricity (30 EJ/yr)
Oceanic	*Scenario-dependent*	1.6 EJ/yr
Wind onshore	*Scenario-dependent*	31.5 EJ/yr
Wind offshore	*Scenario-dependent*	7.9 EJ/yr
Solar PV	*Scenario-dependent*	200 Mha shared on land + PV rooftop endogenous depending on available urban land[a]
Solar CSP	*Scenario-dependent*	
Pumped Hydro Storage	*Scenario-dependent*	31.5 EJ/yr
Annual capacity growth of RES for heat (commercial / non-commercial)		Potential [63]
Bioenergy	+11%/yr / +20%/yr	Shared potential for heat and electricity (30 EJ)
Geothermal	+10%/yr / +15%/yr	139 EJ/yr
Solar thermal	+20%/yr / +20%/yr	Endogenous depending on urban land[a]
Bioenergy		Potential [63]
2nd Gen cropland	+3.5%/yr	200 Mha
3rd Gen cropland (starting 2025)	20%/yr	
Residues (starting 2025)	20%/yr	25 EJ/yr
Non-renewable energies depletion curves		
Oil	[123]	
Gas	[124]	
Coal	Best Guess [125]	
Uranium	[126]	
Climate Change impacts	Logistic energy losses function (a = 700 ppm; b = 50) [43,63]	

[a] Share available roof over total urban land: 5% from current 2-3% [3].

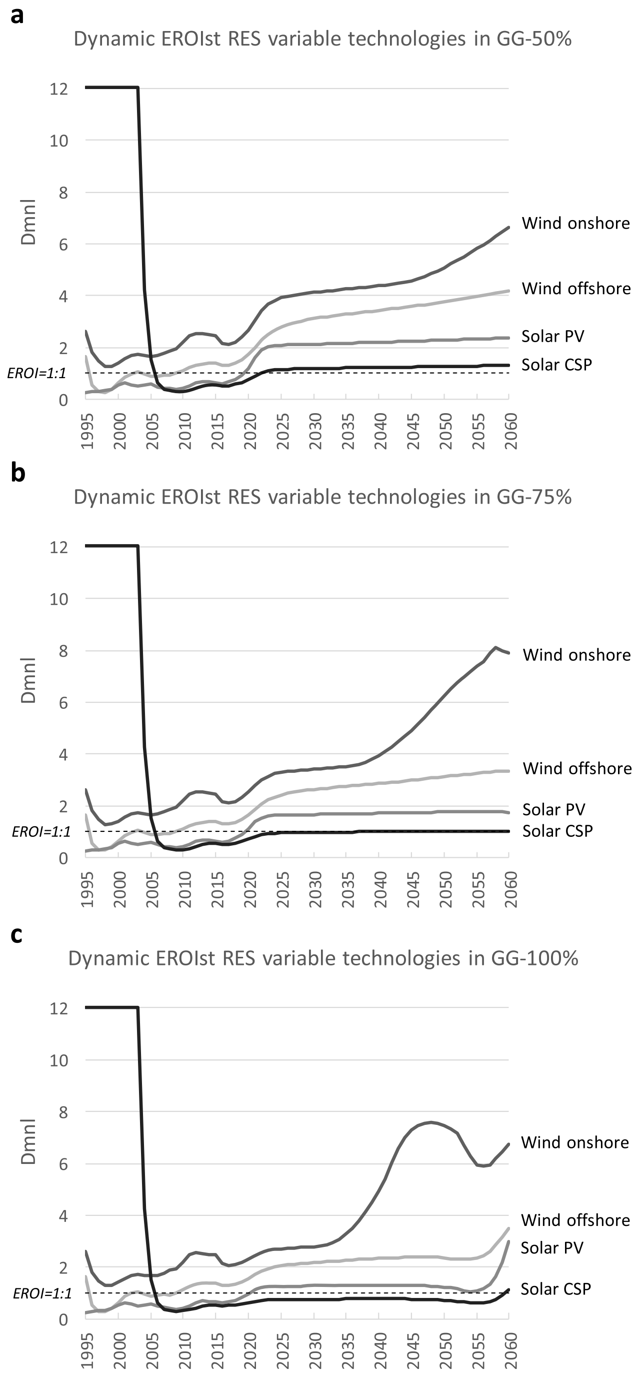

Fig. 4. Dynamic EROIst of the RES variable technologies for the scenarios GG-50% (a), GG-75% (b) and GG-100% (c). CSP starts at a constant ~12:1 level given that no capacity was installed in the period 1995–2005 (required energy investments correspond just with O&M). Dmnl: Dimensionless.

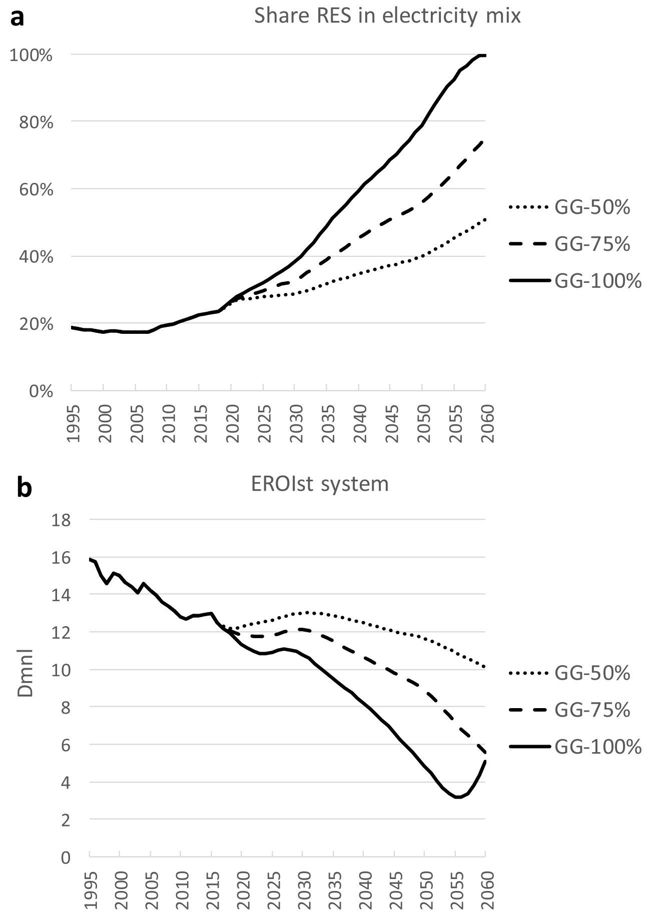

Fig. 5. Transition to RES in the electricity system and EROIst of the full energy system for the scenarios GG-50%, GG-75% and GG-100%: (a) share of RES in the electricity generation mix; (b) dynamic evolution of the EROIst of the energy system. Dmnl: dimensionless.

It is found that wind technologies generally provide more net energy over time to the system than solar ones. In particular, in GG-100% solar technologies would be a clear net contributor to the system only by the end of the simulation period (Fig. 4c). The low dynamic EROIst values in the past (such as < 1:1 for solar technologies) are due to the high energy investment costs as a consequence of the combination of the high material and energy intensities with very fast growth of these technologies in the last two decades. All dynamic EROIst levels tend to increase over time. This is mainly due to the progressive reduction of the growth rate of new RES power plants as their cumulative capacity builds up, which thus increases the instantaneous energy returns; and, to a lesser extent, to the assumed increase of mineral recycling rates within the GG paradigm (i.e., secondary minerals are generally less energy intensive than processing primary minerals from the mine [105]). However, other factors such as the need of overcapacities due to RES intermittency management tend to reduce the EROIst when approaching the 100% RES target (see Supplementary Material). The EROIst of a given technology reaches its maximum value when the full techno-sustainable potential of a resource is under exploitation and then energy investments are dedicated only to infrastructure replacement and O&M, and while the penetration of variable RES has not reached critical levels. This is the case for example of wind onshore in scenarios GG-75% (~2055) and GG-100% (~2040). When RES in the GG-100% scenario achieve to replace non-renewables by the end of the simulation period, the EROIst of all the RES technologies increase substantially, although with a delay due to the inertias in the energy system, given that the fast growth rates of capacity installation of the transition are not any longer necessary (Fig. 4c).

Fig. 5a shows the penetration level of RES in the electricity mix for the 3 scenarios considered, which matches with the targets selected by 2060: ~50%, ~75% and ~100%. Fig. 5b shows the dynamic evolution of the EROIst of the system, which is found to have decreased from ~16:1 in 1995 to ~12:1 in 2015 mainly due to an increase in the energy industry own-energy use as reported by the IEA Balances [84], and to a lesser but increasingly important extent during this period of the penetration of RES electric in the global electricity mix. As expected, the EROIst of the system decreases faster in those scenarios where the penetration of RES in the electricity system is faster. This way, the EROIst for each scenario in 2060 is ~10:1 (GG-50%) and ~5:1 for GG-75% and GG-100%, respectively. The fact that for the latter two scenarios the same EROIst of the system is obtained in the target year is due to the dynamic nature of the transition to renewables: as seen in Fig. 5b, the EROIst for the GG-100% scenario decreases faster than the GG-75% reaching a minimum of ~3:1 at ~2055, increasing thereafter. This behaviour is due to the fact that the EROIst in a given year depends by definition on the energy investments being performed during that year. By 2055, the transition to RES in the electricity sector is almost achieved in the GG-100% scenario and due to this reason the rate of energy investments decreases thereafter thus allowing the EROIst of the system to partially recover (see Fig. 6) until ~5:1. Similarly, scenarios GG-75% and GG-50% also show a "rebound" (although of lower magnitude) during the second half of the 21st century if the timeframe of the analysis is expanded to 2100. The magnitude of this "rebound" depends on the interaction of different factors which are scenario dependent such as the level of electricity demand, the growth rate of new RES facilities, the availability of storage, etc.

The EROIst of the system decreases over time[10] even while the EROIst levels of the individual RES variable technologies have an increasing trend. This is due to the fact that the EROIst levels of the latter are lower than the current EROI of the full system (dominated by high EROI fossil fuels and hydroelectricity), and their share increases over time in the simulated scenarios. Hence, the effect of exponential increase and cumulated capacity of RES for electricity drive the EROI of the system to lower levels.

Fig. 6 shows the total final energy invested by factor for each scenario. From current energy investments < 40 EJ/yr, total final energy invested increase in all scenarios reaching ~60 EJ/yr (GG-50%), ~90 EJ/yr (GG-75%) and ~110 EJ/yr (GG-100%) by 2060. The energy investments associated with the construction and operation of variable renewable technologies for electricity generation (wind, PV and CSP) is the factor contributing most to the increase of total final energy invested during the simulation period. Its share over the total final energy investments increases from current ~5% to ~20% (~13 EJ/yr) in GG-50% and ~40% (~37 EJ/yr) in GG-75% by 2060. In GG-100% a maximum of 70% (~120 EJ/yr) is reached by 2055 followed by a drop to 55% (~40 EJ/yr) five years later. The maximum level of final energy investments in the scenario GG-100% (Fig. 6c) corresponds with the minimum in the EROIst of the system (see Fig. 5b). This is a vast amount of energy investments, amounting to 30% of the current TFEC.

The installation of new capacities represents the majority of investments related with variable renewable technologies for electricity generation (> 70% vs < 30% for O&M, decommissioning and overgrids). Energy storage investments depend on the penetration of variable RES in the electricity mix, requiring < 15% of the total final energy invested for all scenarios. Dispatchable RES require energy investments of 5–10 EJ/yr in all scenarios.

4.1.2. Overdemand estimation and efficiency of the whole system

The decrease in the EROIst 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. As reported in section 2.3, this phenomenon is modelled in MEDEAS-W through a function of overdemand (EROI FC). Fig. 7 shows the increase in total final energy demand to compensate for the decrease of EROIst of the system up to 2060 for the three simulated scenarios. In other words, it shows the implications for the demand of the necessity to divert energy from the rest of the economy to "just" getting energy. In GG-50% scenario, the overdemand increases softly surpassing +2% by 2060 (i.e., EROI FC = 1.02). In GG-75%, there is a faster increase in the

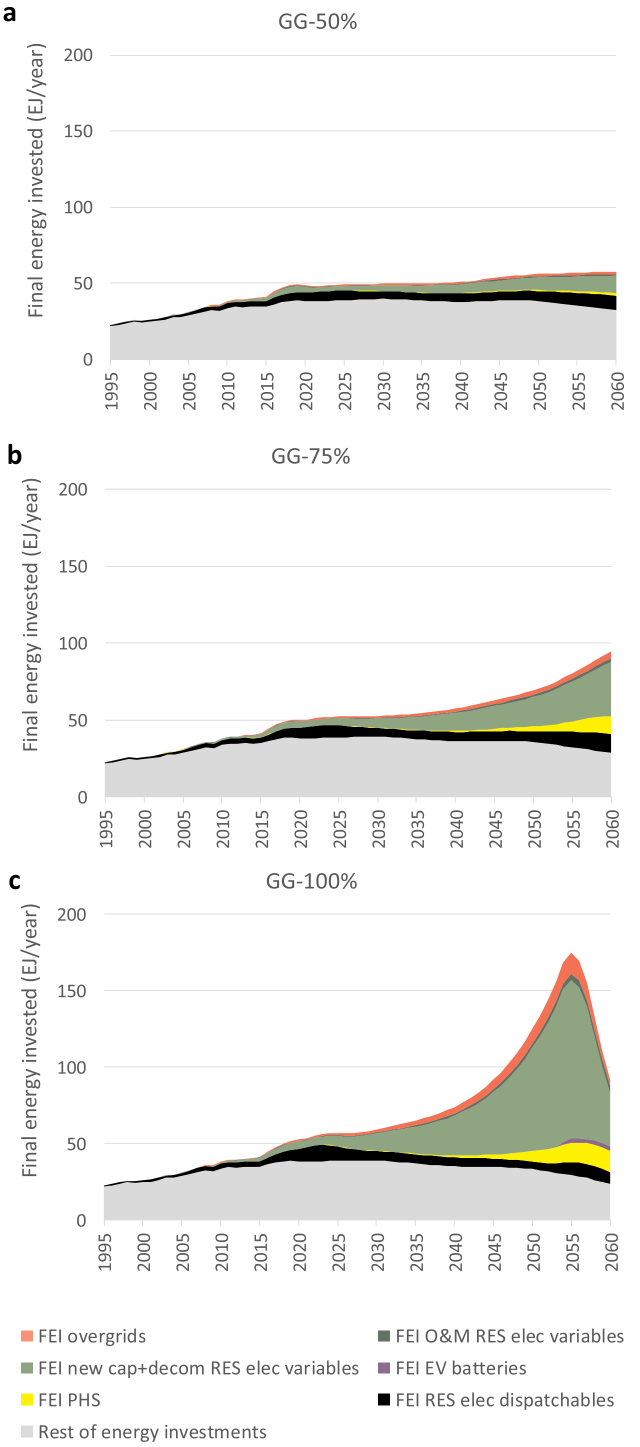

Fig. 6. Final energy invested (FEI) by factor for each scenario (GG-50%, GG-75% and GG-100%): new capacity, overgrids and decommissioning RES variables for electricity generation (new cap + OG + decom RES elec var), operation and maintenance of RES variables for electricity generation –including electricity self-consumption- (O&M RES elec variables), electric vehicle batteries (EV batteries), pumped hydro storage (PHS), RES dispatchables for electricity generation (RES elec dispatchables) and the rest of energy investments (related to non-electric renewables and non-renewable energies).

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[10] The EROIst of the system increases slightly for scenarios GG-50% and GG-75% in the first period of the simulation (2020–2030) due to the fact that the imposed growth rates of RES capacity for the technologies for electricity generation consistent with the 2060-targets are lower than the last recent historical data.

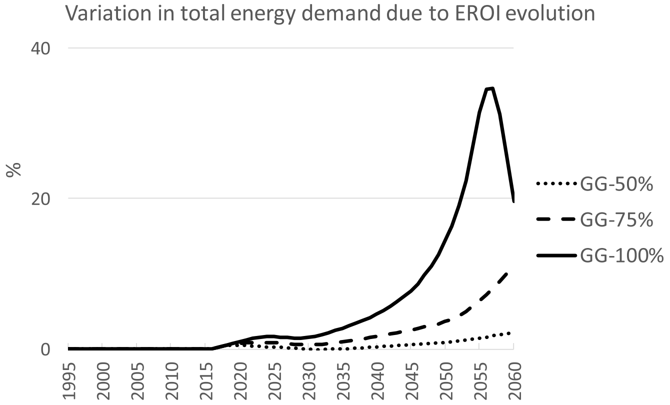

Fig. 7. Variation (%) of total final energy demand due to accounting for the EROI feedback.

overdemand which reaches +11% by 2060. Finally, in GG-100% the effects are very large: there is a maximum of around +35% by 2055, which corresponds with the aforementioned maximum in final energy invested and the minimum in the EROIst of the system. This means that, in order to satisfy the same final net energy demand in GG-100%, the system would need to process 35% more of energy with relation to the case of not accounting for the EROI variation feedback. In the case of assuming no improvement in the recycling rates of minerals during the timeframe studied, the overdemand would reach a peak of +45% (EROIst of the system of 2.8:1 vs 3.2:1).

Hence, the decline in the EROI of the system negatively affects its efficiency. Fig. 8 shows that by 2055 the total final energy intensity (defined as TFEC/GDP) in the GG-100% scenario would reach the level attained in the mid-2020s, while in the case of not accounting for the EROI variation feedback, the total final energy intensity steadily decreases over the simulated period (cumulated reduction of ~40% between 2020 and 2060). For the scenario GG-75%, the total final energy intensity starts to increase by 2050 and by 2060 it reaches the levels of 20 years before (Fig. 8b). These results point to a strong re-materialization of the system during a fast transition to renewable energies which counters the assumed exogenous efficiency improvements for the productive sectors and households assumed within the GG narrative as implemented in this study (see Table 3).

4.1.3. Dynamic EROI of the system: comparison of obtained results with the literature

As aforementioned in the Introduction, few studies have up-to-now analysed projections of 100% RES scenarios from a net energy perspective. Among the exceptions are the following studies: [51,54,58]. Of those, only Sgouridis et al. [58], considers the up-front costs of the energy investments dynamically and the delayed return of energy generation over the lifetime of the infrastructures. Those works applying a "static" approach for EROI integration downplay the transitory reduction in the net energy delivered to the society during the transition to RES.

Also, all previous works have focused on the estimation of a "composite" EROIst of the system obtained as the weighted average of the static EROIst of the different technologies in the energy mix. This approach misses the dynamic nature of the problem as well as the additional infrastructure to manage the intermittency of RES (overgrids, overcapacities and storage). In fact, the intermittency of variable RES in these previous works is represented poorly, most focusing on average annual power. Sgouridis et al. [58], considers additional losses due to the storage of a share of variable generation; however given the specifications considered (ESOI = 125 and storage of 10% of average annual generation), its inclusion does not noticeably affect the results. Trainer [51] does take into account indirectly the overcapacities required in a scenario of 100% electricity for Australia [52]. Further differences between studies are also highly dependent on the estimates of EROIst for each technology considered, given the wide ranges reported in the literature. In this sense, it should be emphasized that the EROIst of the individual electric RES technologies in this study are in the lower range of the literature (see Capellán-Pérez et al. [61]).

Re-running the scenarios GG-50%, GG-75% and GG-100% while

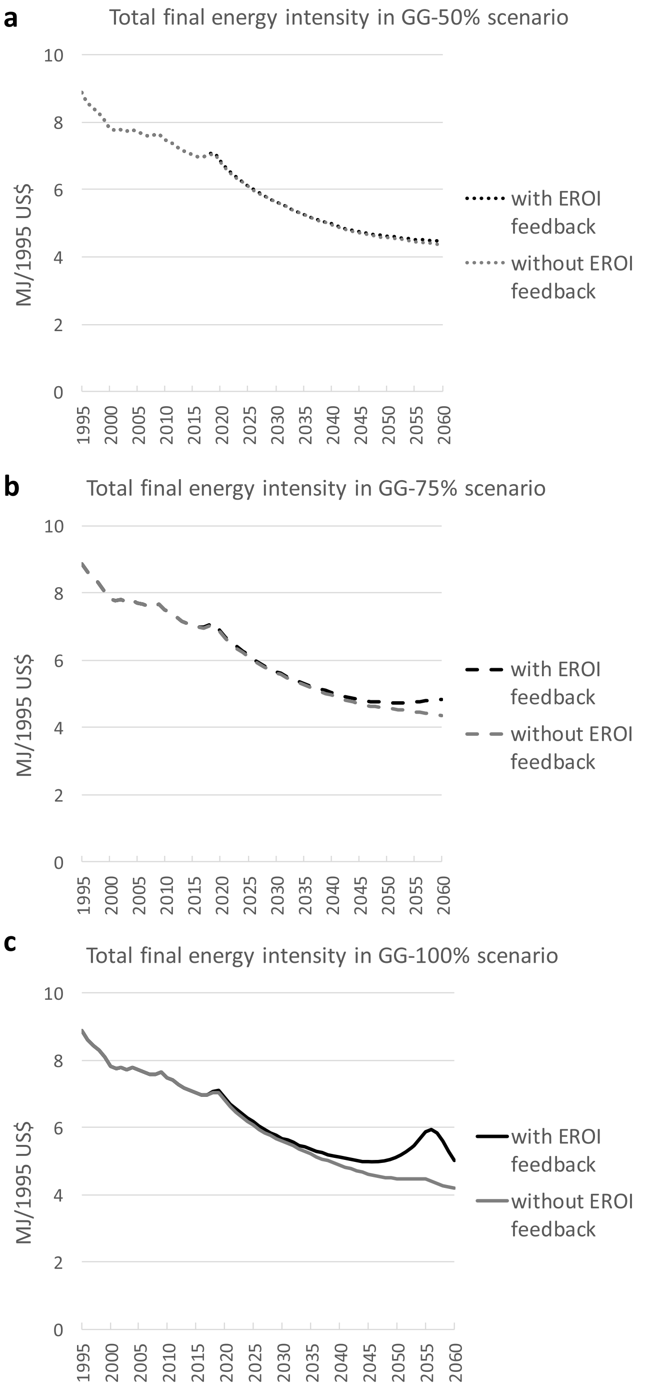

Fig. 8. Comparison of the total final energy intensity in scenario GG-100% accounting for the EROI feedback (black line) and without accounting for its effect (grey line). Total final energy intensity is the ratio between the total final energy consumed in an economy and the total value added (GDP) generated by this economy in a given time period. The EROI feedback factor corresponds to the additional effect on the total final energy required by the system in relation to the reference year (t_0 = 2015) to satisfy the same level of net energy as if the EROI of the system would have not changed (see section 2.3).

considering all the RES for electricity generation as dispatchable resources with the same levels of exogenous capacity growth used before to achieve the 2060-targets, allows us to compute the EROIst of the system in the conditions assumed by the aforementioned studies. First, the removal of the phenomenon of intermittency of variable RES facilitates the transition towards a 100% system considerably, which would occur 10 years earlier for the GG-100% scenario. Similarly, the growth of RES capacity which previously drove the system to ~75% of the electricity generation by 2060, is able under the new conditions to achieve 90% RES electricity by 2060. These results show that those energy models that do not consider the intermittent nature of the scalable RES technologies provide overly optimistic results. Second, as expected, the EROIst of the system also improves, with the minimum for scenario GG-100% being reached at 6:1 by 2045–50.

4.1.4. Implications of the energetic costs of the transition to RES

What are the systemic implications of the results obtained? It is questionable whether a complex system such complex industrial societies could be able to cope with an EROI of the system as low as 3:1, even temporary, as it is the case in the GG-100% scenario. This would put a big stress in the system, requiring society to process larger amounts of primary energy and materials (see Figs. 2 and 7), thus diverting economic, material and human resources from discretionary uses and simultaneously exacerbating mineral depletion and environmental impacts. In fact, the current modelling framework does not capture the full implications of the drop of the EROI of the system to very low levels. In reality, a sharp drop in the EROI of the system to very low levels should induce a collapse of the system endogenously (as for example in Brandt [24]). Few works have dealt with the intricate issue of the minimum EROI to sustain our society. In the words of Lambert et al. [45],: "Certainly history is littered with cities and entire civilizations that could not maintain a sufficient net energy flow [126], showing us that certain thresholds of surplus energy must be met in order for a society to exist and flourish. As a civilization flourishes and grows it tends to generate more and more infrastructure which requires additional flows of energy for its maintenance metabolism". Different works, applying different methodologies [19,45,127], have suggested that a minimum EROIst of the system > 10–15:1 is required to sustain advanced industrial societies, i.e., to support such things as modern healthcare, education, and arts (discretionary spending) in addition to basic needs (e.g., food, shelter, and clothing). This is in agreement with other works based on alternative methods (e.g. Ref. [127]). Brandt [24], on the other hand, find that the energy return must be roughly > 6:1 (EROIpou) to sustain complex societies, which is roughly equivalent to EROIst > 10:1 and EROIext > 2.25:1, although with a large uncertainty. Note that a distinct threshold does not exist given that the reduced availability of discretionary outputs as inter-industry operations become less efficient is a process with cascade, increasing consequences over time involving the different sectors of the economy. In any case, these numbers are roughly consistent with the current EROIst of the global system obtained in this work (~12:1), given the high inequalities in energy consumption and levels of development at global level [11].

Fig. 9 represents the evolution of the EROIst of the system obtained in this work for each scenario and the different levels of systemic-risk as identified in the literature [19,24,127]. Given that EROIst > EROIpou > EROIext and the above discussion, the following risk levels can be identified depending on the EROIst: > 15:1, no risk; < 10–15:1, low risk; < 5–10:1, dangerous; < 5:1: very dangerous; < 2–3:1, unfeasible system. These levels are indicative and evidently the risks are inversely proportional to the EROIst, similarly to the risks identified by the IPCC in the "Reasons for Concern" diagrams ([128,129]). It is noteworthy that, by the mid-century, and even with a renewable share in the electricity sector of ~50%, the system could enter in a zone identified as "dangerous" in the literature.

The reported results are even more upsetting taking into account that a number of conservative assumptions likely make the obtained results optimistic:

- $EROI_{st} > EROI_{pou} > EROI_{ext}$, i.e., Net $energy_{ext}$ < Net $energy_{pou}$ < Net $energy_{st}$.
- Only the dynamic evolution of the EROI of the RES technologies to produce electricity has been considered. The evolution of the EROI of the rest of RES (liquid biofuels, heat) is neglected. Moreover, in the long term, the EROI of non-renewable fuels will tend to decrease due to geological depletion; indeed, recent analyses have found that this trend is already ongoing, trends which will be exacerbated by the growing share of unconventional fuels characterized by lower EROI [9,36,49,50].
- Generous recycling improvement rates of minerals are considered

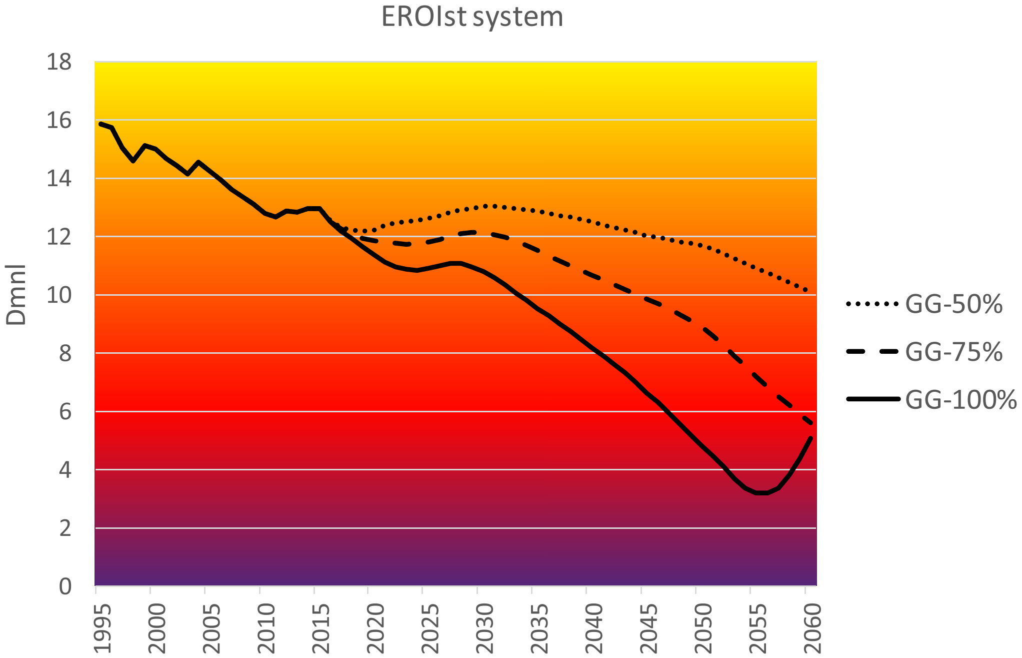

Fig. 9. Dynamic evolution of the EROIst of the full energy system for the scenarios GG-50%, GG-75% and GG-100% and different levels of systemic-risk as identified in the literature. These levels are indicative and evidently the risks are inversely proportional to the EROIst, similarly to the risks identified by the IPCC in the "Reasons for Concern" diagrams ([128,129]). Dmnl: dimensionless.

within the GG narrative to reach very high rates by 2060 (85%), requiring a full and rapid paradigm shift in product design [69]. Moreover, phenomena of opposite trend such as the increase in energy requirements due to the ore decrease of minerals [41,42] may more than compensate for this in the future.

This work focuses on the global level, whose results are also qualitatively translatable to regional and national level given the similarities between current energy systems in different countries (i.e. centralized systems highly dependent on fossil fuels) and the common challenges they face to successfully achieve the transition to renewable energy sources (RES). Analyses focusing on the regional/national scale might refine the results given that those ultimately depend on geographical conditions, such as the potential and quality of each RES technology as well as on national policy decisions such as the selected strategy to deal with the variability and intermittency of RES variables.

Finally, the EROI of the system is ultimately dependent on the mix of technologies in the electricity supply as well as on the strategy and options available to deal with RES intermittency. Further work may be directed to design a robust technology allocation methodology within the model which takes into account the relative EROIst of different options in order to allow to simulate scenarios avoiding the situation in which the EROI of the system is drained by a high participation in the energy mix of those technologies with a lower EROIst. Nevertheless, it should also be kept 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.

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, Input-Output analysis seems a promising approach [36,46].

A business-*as*-usual (BAU) scenario has deliberately not been included in this work for the purpose of clarity, in order to facilitate the description and explanation of the factors and mechanisms factors affecting the computation of the EROI of the system. In any case, a BAU scenario would not be presumable more viable than a GG considering other constraints such as climate change damages. Further work will be

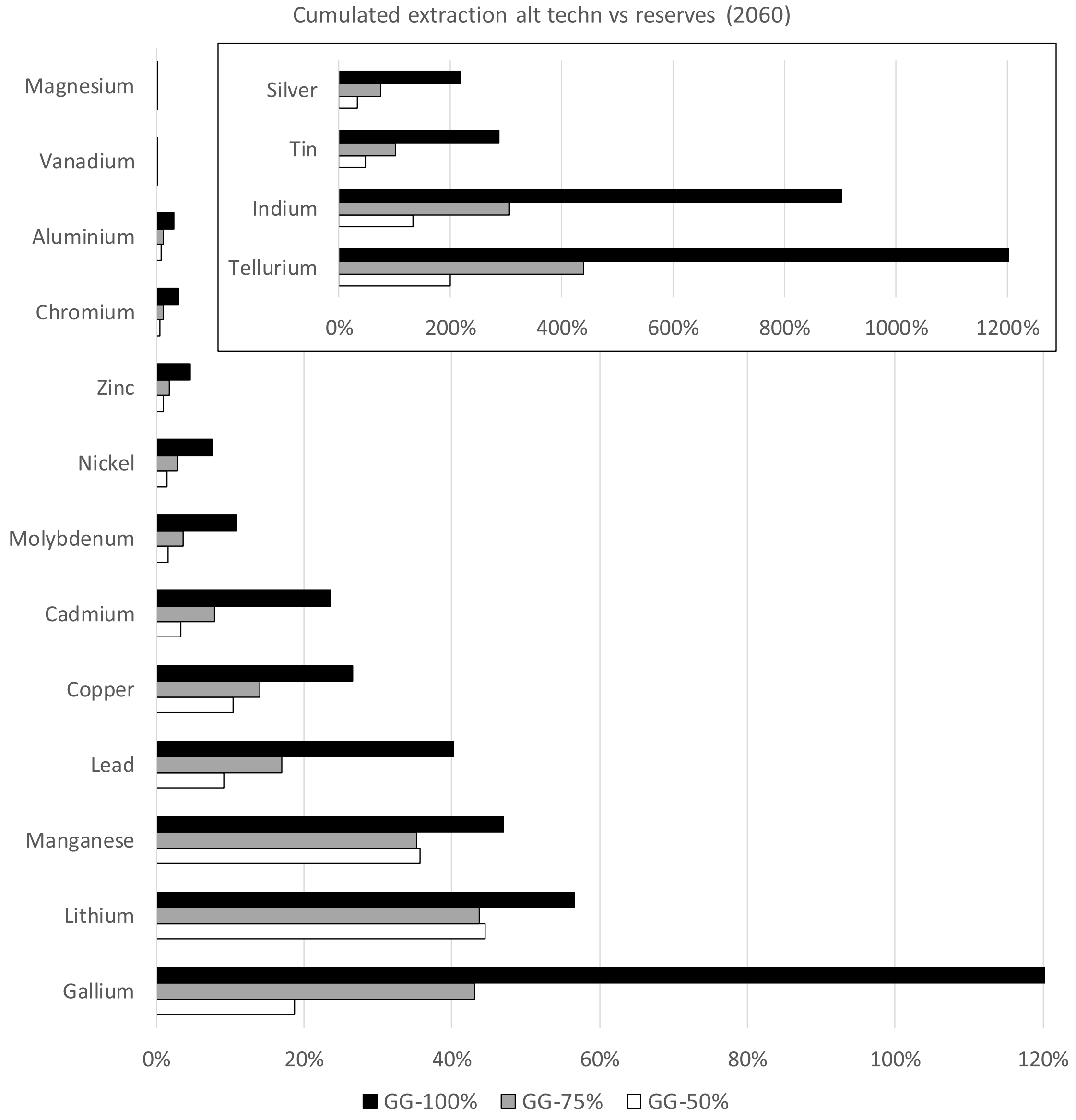

Fig. 10. Cumulated extraction (2015–2060) of minerals for alternative technologies vs current estimated reserves for the three scenarios GG-20%, GG-50% and GG-100%.

directed to comprehensively compare this and other representative scenarios in the literature [114,130,131] across all dimensions considered in MEDEAS framework (see Appendix A).

4.2. Material requirements

There are large uncertainties in relation to the future availability of minerals, the usual reserves and resources estimates being even more problematic than those of fossil fuels. Robust estimates of their availability in the literature to date are scarce and limited to few minerals (e.g. Refs. [132–134]). In fact, although the concept of "peak oil" and other fossil fuels has been explored and debated extensively within the literature, there has been comparatively little research examining the concept of "peak minerals" [135–137]. For these reasons, the supply of minerals (conservatively) does not constraint the system in MEDEAS-W, as it is done, for example with fossil fuel availability [107].

In order to assess the implications in terms of eventual future scarcities, the cumulative mineral extraction from mines over the studied period is compared with their current level of reserves and resources (as performed by other studies e.g. Refs. [64,74]). Generally, the term "resources" is used to represent the amount of energy resources (proven or geologically possible), which cannot currently be exploited for technical and/or economic reasons but may be exploitable in the future. "Reserves" refer to the fraction of the resource base estimated to be economically extractable at the time of determination. Currently, one of the most used sources for reserve, reserve base and resource information is the USGS, as it compiles information from mines and deposits from all over the world and for a wide set of mineral commodities. Yet, the information is sometimes incomplete or inaccurate. Table B.2 shows the reserves and resources information for the commodities selected in this study, which is the result of the comparison of different sources and selection of the best and most accurate data [134,138–141] (see Table 1 in Ref. [142]).

Fig. 10 shows the ratio between the cumulated extraction (2015–2060) of minerals for the alternative technologies and the current reserves for the three scenarios considered in this study. By the end of the period, the cumulated primary demand is higher than the current estimated level of reserves for 5 minerals in at least one of the

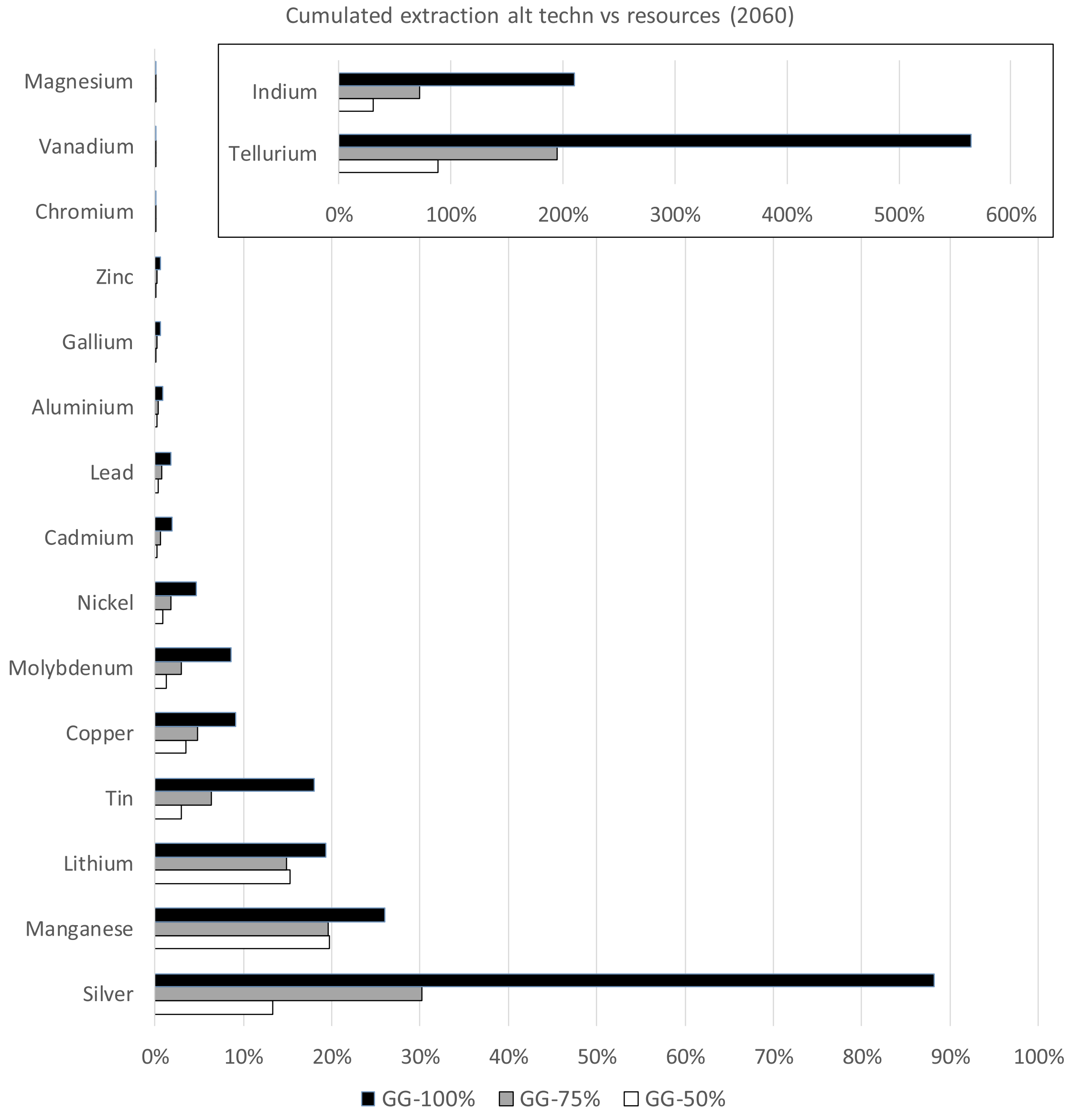

Fig. 11. Cumulated extraction (2015–2060) of minerals for alternative technologies vs current estimated resources for the three scenarios GG-20%, GG-50% and GG-100%.

considered scenarios: tellurium, indium, tin, silver and gallium. Four more minerals would require at least ¼ of the current reserves: lithium, manganese, lead and copper.

Fig. 11 shows the ratio between the cumulated extraction (2015–2060) of minerals for alternative technologies and the current resources. By the end of the period, the cumulated primary demand is higher than the current estimated level of resources for two minerals in at least one of the considered scenarios: tellurium and indium. Two more minerals would require at least ¼ of the current resources: silver and manganese.

Following these results, the most affected technologies by mineral scarcity would be some solar PV technologies (tellurium, indium, silver, manganese), solar CSP (silver, manganese) and Li batteries (lithium, manganese). Wind technologies would be much less affected. Notably, gallium and indium also belong to the list of 14 critical minerals identified by the Raw Material Initiative of the EU [72]. These results also show that the transition to alternative technologies will intensify global copper demand, "the backbone of the telecommunications infrastructure in the global North" [143], by requiring 10–25% of the current reserves and 5–10% of the current resources of copper globally (note that only overgrids for connecting additional variables RES power plants and interregional grids (HVDC) and have been modelled in the analysis). For example, other studies considering a full transition to 100% RES and considering the material requirements for transportation of electricity reach higher levels, e.g., 60–70% of estimated current reserves [74].

Ideally, dynamic demand should be compared with dynamic supply, which is beyond the scope of the current work (e.g. Refs. [64,144]). The consideration of static metrics such as reserves and resources provides a lower bound for risk analysis. However, given the involved uncertainties, the viability of extracting current resources cannot be assured. Another conservative assumption is the hypothesis of high growth of recycling rates of minerals in the next decades. Moreover, given that we are using the Recycled Content (RC) definition for recycling rates, we are a priori assuming the availability of sufficient waste mineral to be reintroduced in the system, which may not be always the case, especially for those minerals for which a strongest increase in demand is expected in the next decades.

Finally, it should be kept in mind that the interaction with the demand of minerals from other sectors of the economy would worsen the aforementioned assessment. However, the low quality of data in relation to mineral consumption by the whole economy globally prevents us from performing a robust projection of these material requirements in the future [64]. Still, a sensitivity analysis has been performed considering that the demand of minerals linearly depends from GDP evolution (see Appendix B.1). We believe this approach, despite the uncertainties and aforementioned low quality data involved, allows us to capture first-order magnitude effects. Appendix B.2 shows the results in terms of cumulated extraction (2015–2060) vs current reserves (Fig. B1) and resources (Fig. B2). As expected, the risk analysis substantially worsens: by the end of the period, the cumulated primary demand is higher than the current estimated level of reserves for 12 minerals in at least one of the considered scenarios: tellurium, indium, tin, silver, gallium, lead, zinc, manganese, nickel, copper, molybdenum and cadmium. Three more minerals would require at least ¼ of the current reserves: chromium, lithium and vanadium. By the end of the period, the cumulated primary demand is higher than the current estimated level of resources for 3 minerals in at least one of the considered scenarios: tellurium, indium and silver. Six more minerals would require at least 1/4 of the current resources: manganese, molybdenum, nickel, copper, tin, and zinc. Recent empirical research confirms some of these findings. For example, it has been found that the recent global deployment of PV has driven higher silver prices [145]. In fact, our results indicate that ~18% of the total demand of silver in 2016 was required by solar PV.

Hence, the extraction of the minerals required to fuel a global GG development will likely intensify the current socio-environmental conflicts related with the expansion of the extraction frontier globally [146]. Impacts associated with the mining of key metals used in renewable energy and storage include pollution and heavy metal contamination of water and agricultural soils, and health impacts on workers and surrounding communities [147]. The assessment of the potential impacts generated by the development of new mines could be the focus of further work (identification of the most vulnerable countries and communities, etc.). Certification schemes looking to ensure responsible sourcing of minerals could be extended to all minerals creating a minerals 'Fair Trade' (Earthworks, Fairtrade International). However, analyses of with current schemes point that they generally have little benefit for the poor producers [148–150].

The main way to overcome supply bottlenecks and socio-environmental impacts in a business-*as*-usual or GG paradigm is through improving recycling rates of metals. This can be very difficult, due to several factors such as unappropriated design, special properties which need complex recovery processes and when mixed, thermodynamic limits, etc. [64]. Hence, plausible alternatives would consider demand-side options in the line of voluntary lower material consumption [151] or wider reaching proposals such as the resource cap initiative [152].

5. Conclusions

In this work, a novel methodology is applied to assess the energy and material investments required in the next decades to achieve the transition from fossil fuels to renewable energy sources (RES) in the electricity sector. The developed approach, implemented in the MEDEAS modelling framework [61], includes a number of novel methodological contributions in relation to the state-of-the art of energy systems and Energy Return on energy Invested (EROI) analysis, allowing us to reconcile some of the extant discrepancies in the literature (e.g. Refs. [14,27,30–32,34,35]): (1) the dynamic and endogenous approach allows us to more realistically capture the intrinsically dynamic phenomenon of the up-front costs and delayed returns over the lifetime of the transformation of the energy system, thus overcoming the limitations of the usual static approaches; (2) the required overcapacities, overgrids and storage in high RES penetration scenarios are assigned to the whole energy system instead to a specific technology; and (3) the incorporation of the implications of the variations in the EROI of the system for the whole system.

The results we reported here are global, although the main implications can also be translated to regional and national level given the similarities between current electricity systems and the common challenges they face to successfully achieve this transition to RES and alternative technologies. On the one hand, those RES with a higher potential (i.e. wind, solar) have been generally found to have lower EROI standard (EROIst) than fossil fuels, especially when incorporating the energy costs of dealing with intermittency. On the other hand, 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.

The results obtained in this work indicate that achieving high penetration levels of renewables in the electric system by 2060 consistent with the *Green Growth* narrative would decrease the EROI standard (EROIst) of the entire global system from current ~12:1 to between ~3 and 5:1 by the mid-century. These EROI levels are well below the thresholds identified in the literature required to sustain high levels of development in current industrial complex societies [19,24,30]. This would translate into a substantial energy overdemand reaching a peak of +35% during the transition for the case of 100% RES; i.e. the production of energy would need to increase by 35% in order to supply the same level of net energy to society during the transition to RES. The increase in energy investments would imply a higher primary energy consumption which in turn would intensify the issues of environmental impacts and resource depletion. Hence, if not properly managed, the transition to RES could imply a strong reduction in the net energy available for society. In relation to material investments, the obtained results show that RES deployment would require a substantial amount of minerals relative to the current estimated levels of reserves and resources, driving in fact a substantial re-materialization of the economy which would exacerbate eventual mineral risk availability in the future. In particular, estimated cumulated extraction demand would surpass the current level of reserves in GG-100% for tellurium, indium, tin, silver and gallium. As a corollary the results obtained put into question the consistence and viability of the *Green Growth* narrative [76–81]. This work also contributes to the novel research field focusing on the biophysical implications of the large upscaling of modern renewables [3,160,161].

The dynamic and endogenous computation of the EROI of the system represents a key novelty in relation to the current state of the art in energy modelling, given that most models used for advising policy (e.g. IEA, IPCC, national governments, etc.) neglect the energy investments related with the construction and operation of the RES power plants, as well as the implications on the full energy system. The relation of EROI to net energy is non-linear (i.e., the “net energy cliff”), and consequently its impact can potentially be misjudged. To our knowledge, very few models take a net energy approach (GEMBA [54]; NETSET [58]; EETRAP [21]), and the studies considering alternative methodologies of technology allocation other than minimizing monetary costs based on biophysical criteria such as their relative EROI are to date scarce (e.g. Ref. [53]).

Summarizing, this work has three main implications:

- In terms of planning the transition to RES, it is usually assumed that the only relevant constraints are political and economic (i.e., political will and monetary investments). However, the results presented in this work show that the EROI of the system is also a relevant factor to be considered when assessing the best choices for the deployment rates of RES technologies. There is a trade-off between urgent climate mitigation and viability of the system. Moreover, decreasing (monetary) learning rates might not correspond to real technological improvements (e.g. Ref. [38]). Hence, it is necessary for energy modelling to complement classical monetary costs (e.g. Refs. [1,39,60,109,153–155]) with biophysical quality indicators such as the EROI [156].
- From the point of view of the efficiency of the system, the results obtained show that a strong transition to RES would imply a rematerialization of the economy with the potential to counteract future efficiency improvement trends, a factor which is not considered in most energy-economy models [1,60,109,112,157,158].
- Material availability may pose problems to the deployment of some RES and alternative technologies in the next decades, especially in the case of solar technologies. A recycling-friendly design of products and technologies is key to make possible high recycling rates in the future [64].
- Finally, from a policy perspective, the aforementioned factors such as the resulting EROIst of the system being well below the range of the thresholds identified in the literature as necessary to sustain high levels of development in current industrial and complex societies, as well as the evidence of the strong re-materialization required to perform the transition towards RES energies in the electricity sector (instead of absolute decoupling), put into question the consistence and soundness of the *Green Growth* paradigm as it is being currently presented [76–81].

As any modelling study, this work presents a number of limitations which may be addressed in future work. First, the application of recycling rates as recycled content (RC) assumes the availability of stock of minerals in the economy ready to be recycled, which in an expanding economy it may not be always the case. Second, only the dynamic evolution of the EROI of the RES technologies to produce electricity has been considered, further work will be focused towards expanding the dynamic representation of EROI to all energy sources and technologies within the MEDEAS-World (MEDEAS-W) model. Third, ideally the EROI feedback should be driven by the concept of EROIext (or EROIpou) instead of EROIst; further progress may be directed to broadening the boundaries to estimate an EROIpou of the system including the full energy investments associated with the distribution of energy. Fourth, 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, a sharp drop in the EROI of the system to very low levels should endogenously induce a collapse of the system (as for example in Brandt [24]). An option would be to explicitly model the link between the energetic investments in the energy module and the related monetary investments in the economy module of the MEDEAS-W model (as performed for example by Refs. [21,54]). Fifth, further work may be directed to improve data reliability of the grades, reserves and energy cost of minerals with two aims: (1) robustly feed-back the availability of minerals to the economic processes, e.g. via introduction of mineral depletion curves as it is currently done with fossil fuel availability; and (2) model the increase in energy requirements due to ore decrease of minerals [41,42]. Given uncertainties and lack of reliable data, further work could be directed to one or few minerals for which data availability is currently more robust (e.g. copper [106,133]). Sixth, the use of representative technologies prevents from analysing the role of technology replacement to deal with eventual mineral scarcities [116]; however a consistent analysis should take into consideration that more abundant materials tend to reduce the technical performance [93,159]. It is noteworthy that the first five aforementioned limitations bias results towards conservative results, i.e. its integration in the modelling framework would increase the constraints on the system.

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 among declining EROI of the system levels with other key factors such as climate change impacts, non-renewable energy resources availability, or demand-management policies going beyond the usual technological policies. This comprehensive analysis should allow to build normative scenarios in which the trade-off between climate mitigation and viability of the system is achieved while avoiding potential “energy trap” scenarios.

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Appendix A. Modelling framework of MEDEAS

MEDEAS-World (MEDEAS-W) is a global, one-region energy-economy-environment model (or integrated assessment model). It is a policy-simulation dynamic-recursive model which has been designed applying System Dynamics,[11] 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 nine main submodules: Economy, Energy demand, Energy availability, Energy infrastructures & EROI, Minerals, Land Use, Water, Climate and Social and Environmental Impacts Indicators (see Fig. A1). The main variables that connect the different modules are represented by arrows.

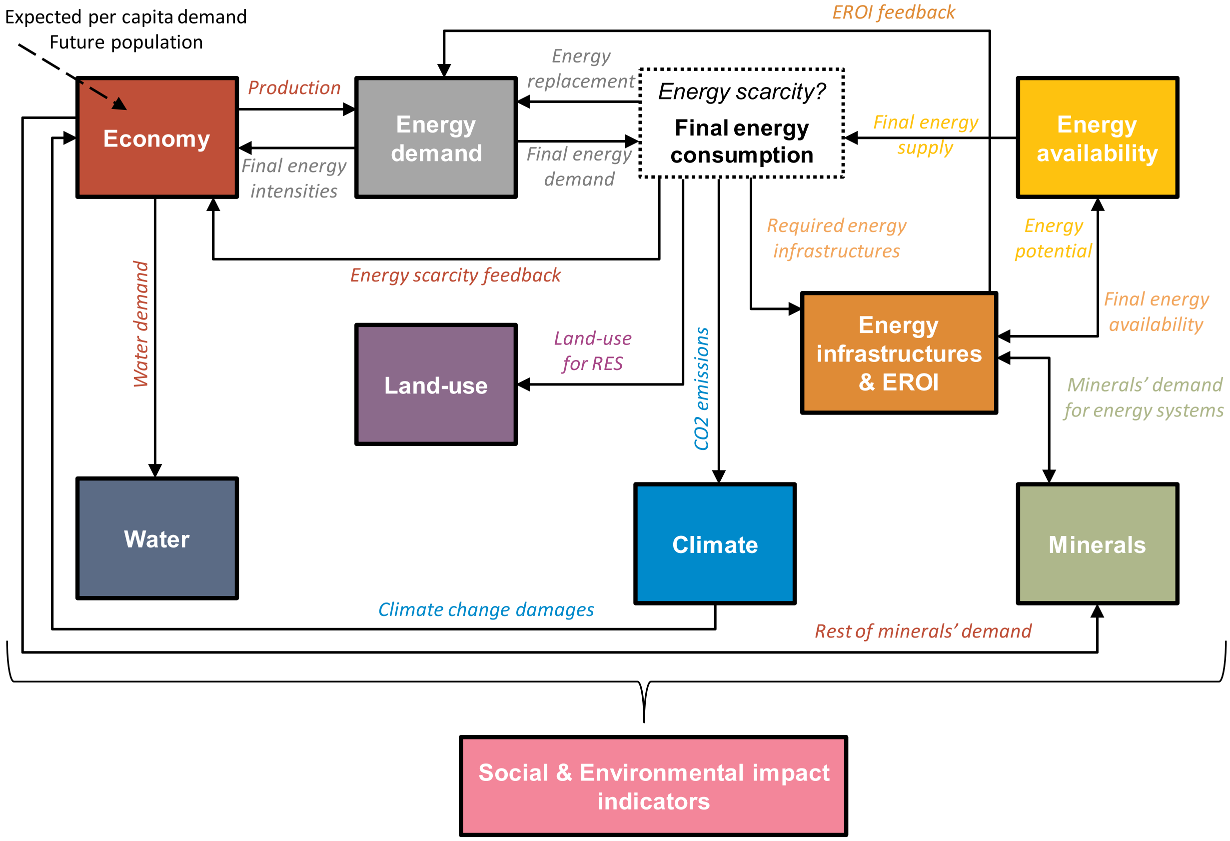

Fig. A1. MEDEAS-World model schematic overview. The main variables connecting the different modules are represented in italics and by solid arrows. The dashed arrow represents the exogenous driver inputs. EROI: Energy return on energy investment. RES: renewable energy sources. Source: adaptation from Ref. [61].

The main characteristics of each module are:

- Economy: the global economy in MEDEAS is modelled assuming non-clearing markets (i.e., not forcing general equilibrium), demand-led growth and complementarity instead of perfect substitutability. Hence, production is determined by final demand and economic structure, combined with supply-side constraints such as energy availability. The economic structure is captured by the adaptation and dynamic integration of global WIOD input-output tables, resulting in 35 industries and 4 institutional sectors [162]. Final energy intensities by sector are obtained by combining information from the WIOD environmental accounts [163] and the IEA Balances (2018).
- Energy demand: Final energy demand by sector and households is estimated through the projection of sectoral economic production and sectoral final energy intensities considering efficiency improvements and inter-final energy replacements driven by policies.
- Energy availability: this module includes the potential and availability of renewable and non-renewable energy resources, taking into account biophysical and temporal constraints. In particular, the availability of non-renewable energy resources depends on both stock and flow constraints [124,164,165]. In total, 25 energy sources and technologies, and 5 final fuels are considered (electricity, heat, solids, gases and liquids), with large technological disaggregation. The modelling of energy availability is mainly based on the previous model WoLiM [130]. The intermittency of RES is considered in the framework, computing endogenous levels of overcapacities, storage and overgrids, depending on the penetration of variable RES technologies.
- Energy infrastructures & EROI. Representation of the capacities for generating electricity and heat, considering planning and construction delays. The energy investments for renewable energies for producing electricity are endogenously and dynamically modelled, which allows to compute the Energy Return on Energy Investment (EROI) of individual technologies and the EROI of the whole energy system. The demand of energy is

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[11] 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/.

affected by the variation of the EROI of the system. Transportation is modelled in great detail, differentiating between different types of vehicles for households, as well as freight and passenger inland transport
- Minerals: minerals are required by the economy, with emphasis on those required for the construction and O&M of alternative energy technologies. Recycling policies are available.
- Land-use: this module mainly accounts for the land requirements of the RES energies.
- Water: this module allows calculating water use by type (blue, green and grey) by economic sector and for households.
- Climate: this module projects the climate change levels due to the GHG emissions generated by human societies (non-CO2 emissions are exogenously set, taking RCPs scenarios as reference [166]). The carbon and climate cycle is adapted from C-ROADS [167,168]. This module includes a damage function which translates increasing climate change levels into damages for the human systems.
- 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, a sectoral economic demand is estimated from exogenous pathways of expected Gross Domestic Product per capita (GDPpc) and population evolution. The final energy demand required to meet production is obtained using energy-economy hybrid Input-Output Analysis, and combining monetary output and energy intensities by final energy source. The Energy availability sub-module computes the available final energy supply, which may satisfy (or not) the required demand: the economy adapts to eventual fuel scarcity. The materials required by the economy with emphasis on those required by alternative green technologies are estimated, which allows to assess eventual future mineral bottlenecks. However, for the sake of simplicity mineral availability does not constrain economic output in the current models' versions. The new energy infrastructures require energy investments, whose computation allows us to estimate the variation of the EROI of the system, which in turns affects the final energy demand. The climate sub-module computes the GHG emissions, whose accumulation derives in a certain level of climate change, which in turn feeds back to the economic sectoral output. Additional land and water requirements are accounted for. Finally, the social and environmental impacts are computed.

The model applied in this study corresponds with an adapted version of MEDEAS-W_v1_2_21. Despite the many interactions and submodule dependencies, the scenarios developed for this work have been set up in a way that the large majority of the differences in outputs are driven by the different assumptions on RES penetration levels in the electricity sector.

Appendix B. Consumption of materials by the whole economy

The demand of materials in MEDEAS-W is split in 2 categories: (1) materials demanded by alternative technologies solar PV, solar CSP, wind onshore, wind offshore, electric vehicle batteries and electric grids, and (2) materials demanded by the rest of the economy. Section B.1 documents the method applied to estimate the demand of minerals from the rest of the system, and section B.2 shows the cumulated extraction of minerals to supply total system demand vs current reserve and resource estimates.

B.1. Demand of minerals from the rest of the system

Most studies analyzing the material requirements of the transition to "green" technologies at global level do not take into account the future demand of the rest of the economy, likely given the lack of robust data which hinders its estimation (e.g. Refs. [64,73,74]). In this work, given the lack of data of material intensities associated to the WIOD sectors [162,163],[12] a stylized approach was applied in order to estimate the consumption of minerals by the rest of the economy acknowledging that there is a close relationship between economic activity and mineral consumption in the current socio-economical industrial system [169,170]. In particular, we assume that the total demand of minerals in the global economy (from primary and secondary production) depends linearly on GDP evolution:

$$Demand\ mineral_i(t) = a_i \bullet GDP(t) + b_i \tag{20}$$

Historical data of the global GDP [171] and of mineral primary production from the United States Geological Service (USGS) [172] for the period 1990–2016, combined with estimates of recycling rates (recycled content) from UNEP [92], are applied to estimate the parameters of the linear regression of the Eq. (20) for each mineral considered in MEDEAS. A correction was included in order to avoid double-accounting in the historic period of the materials required by alternative technologies. It should be highlighted that the data collated by USGS and UNEP at global level suffer from a lack of robustness (e.g., no standardization in the reported categories, lack of information for certain countries and/or minerals (e.g. Nd, Ti, Te), large uncertainty ranges for recycling rates for certain materials, etc.). As a consequence, projections of demand of iron/steel and titanium by the rest of the economy could not be estimated. Most regressions show a good correlation between GDP and material consumption (which is corroborated by high r^2 values, see Table B1), and hence are considered to be a good first order estimate of mineral demand levels of the rest of the global economy for the following decades.

The demand of minerals for fossil fuel plants avoided due to the transition to renewable energies is for the sake of simplicity not taken into account given the much higher material intensity of renewable energies (ranging from x2 to 1 or 2 magnitude orders higher), as well as to the higher diversity in the use of minerals [65–67].

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[12] An alternative Input-Output database including sectoral mineral intensities is EXIOBASE (e.g. Ref. [67]).

Table B1

Parameters and squared-correlation coefficients obtained from linear regression from Eq. (20) relating total mineral demand and GDP at global level.

	a	b	r^2
	(tonnes/T$)	(tonnes)	(Dmnl)
Silver (Ag)	328.91	7599.85	0.903
Aluminium (Al)	1,418,922.86	−30,056,858.88	0.960
Cadmium (Cd)	69.83	16,338.43	0.380
Chromium (Cr)	198,972.69	−3,904,104.71	0.910
Copper (Cu)	296,737.49	−410,662.57	0.984
Galium (Ga)	13.87	−545.34	0.681
Indium (In)	12.00	−278.20	0.594
Lithium (Li)	450.93	−11,006.21	0.888
Magnesium (Mg)	27,176.96	−658,224.56	0.945
Manganese (Mn)	430,051.84	−7,026,661.98	0.851
Molybdenum (Mo)	6601.83	−105,284.12	0.897
Nickel (Ni)	59,354.48	−959,348.43	0.826
Lead (Pb)	138,709.24	−191,827.63	0.920
Tin (Sn)	1781.43	210,900.66	0.285
Tellurium (Te)[a]	0.50	84.96	0.011
Vanadium (V)	1428.80	−27,648.61	0.964
Zinc (Zn)	228,745.78	−113,370.69	0.960

[a] Reported data for Te by USGS represent and underestimation.

The ultimate amount of minerals to extract from mines is also dependent on recycling rates, which is an input of scenario configuration (see Table 3).

Table B2 shows the considered current recycling rates of minerals, estimated level of reserves and resources, consumption and primary extraction.

Table B2

Current recycling rates of minerals (RC, recycled content), estimated level of reserves and resources, consumption and primary extraction.

	Current recycling rates (RC)[a]	Reserves	Resources	Consumption alternative technologies (2016)	Consumption rest of the economy (2016)	Primary extraction (2016)
	UNEP [92]	Task 2.2.c.2 [142]		own estimation	own estimation from USGS [172] and UNEP [92]	own estimation from USGS [172] and UNEP [92]
	share	Mt	Mt	tonnes/yr	tonnes/yr	tonnes/yr
Aluminium (Al)	0.35	28,000.00	75,000.00	3,555,210	87,060,175	58,900,000
Cadmium (Cd)	0.5	0.50	6.00	640	23,260	11,950
Chromium (Cr)	0.19	480.00	12,000.00	60,900	11,418,632	9,298,421
Copper (Cu)	0.285	720.00	2100.00	1,080,740	23,271,659	17,411,965
Galium (Ga)	0.375	0.01	1.00	30	570	375
Indium (In)	0.375	0.01	0.05	470	210	425
Lithium (Li)	0	13.50	39.50	10,980	27,020	38,000
Magnesium (Mg)	0.33	2400.00	12,000.00	9590	1,482,947	1,000,000
Manganese (Mn)	0.37	570.00	1030.00	575,780	24,344,855	15,700,000
Molybdenum (Mo)	0.33	11.00	14.00	5540	410,878	279,000
Nickel (Ni)	0.35	81.00	130.00	36,300	3,179,085	2,090,000
Lead (Pb)	0.525	87.00	2000.00	301,760	9,466,412	4,639,882
Silver (Ag)	0.26	0.53	1.31	4960	29,770	25,700
Tin (Sn)	0.22	4.80	76.20	61,610	307,621	288,000
Tellurium (Te)[b]	0	0.01	0.03	500	123	623
Vanadium (V)	0	15.00	63.00	50	78,950	79,000
Zinc (Zn)	0.225	230.00	1900.00	57,880	16,200,185	12,600,000

[a] Mean of the minimum and maximum values if a range is reported. For those minerals for which no data was found, a RC of 0% is assumed.

[b] Reported data for Te by USGS represent and underestimation.

B.2. Cumulated extraction of minerals to supply total system demand vs current reserve and resource estimates

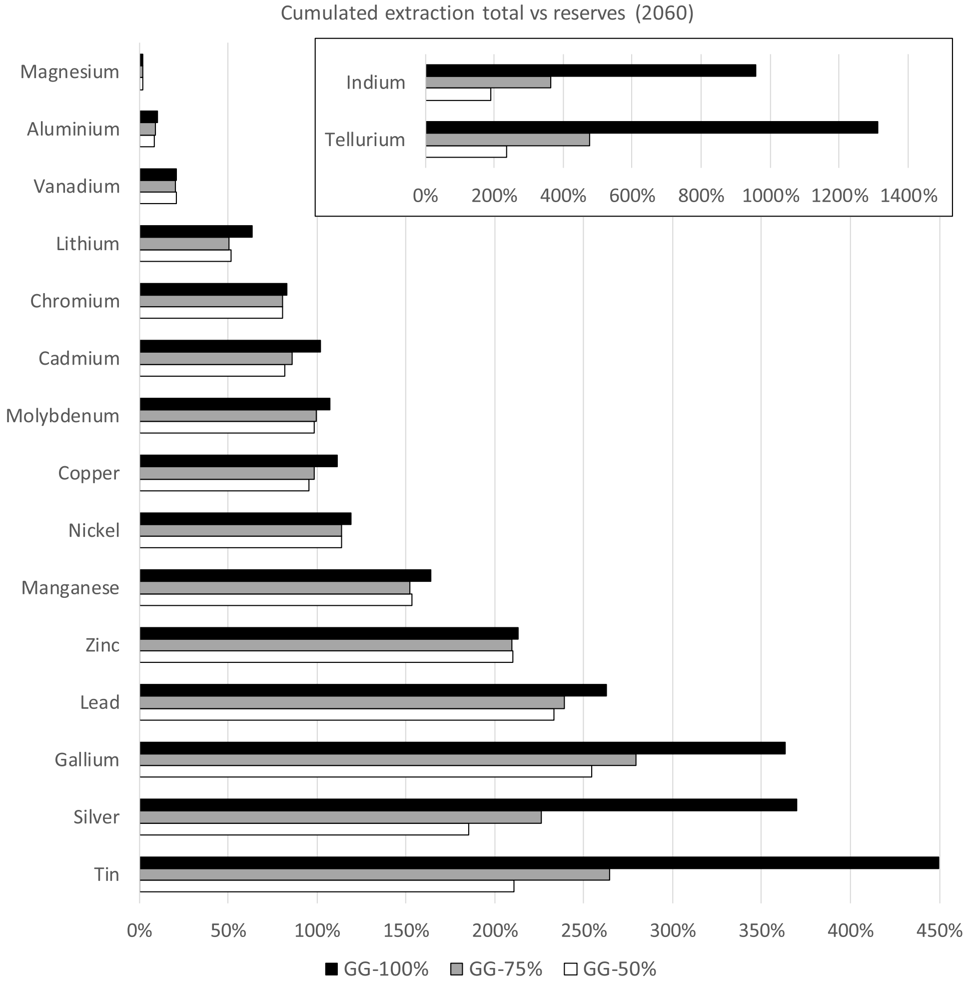

Fig. B1. Cumulated extraction (2015–2060) of minerals for the total system vs current reserves for the three scenarios GG-20%, GG-50% and GG-100%.

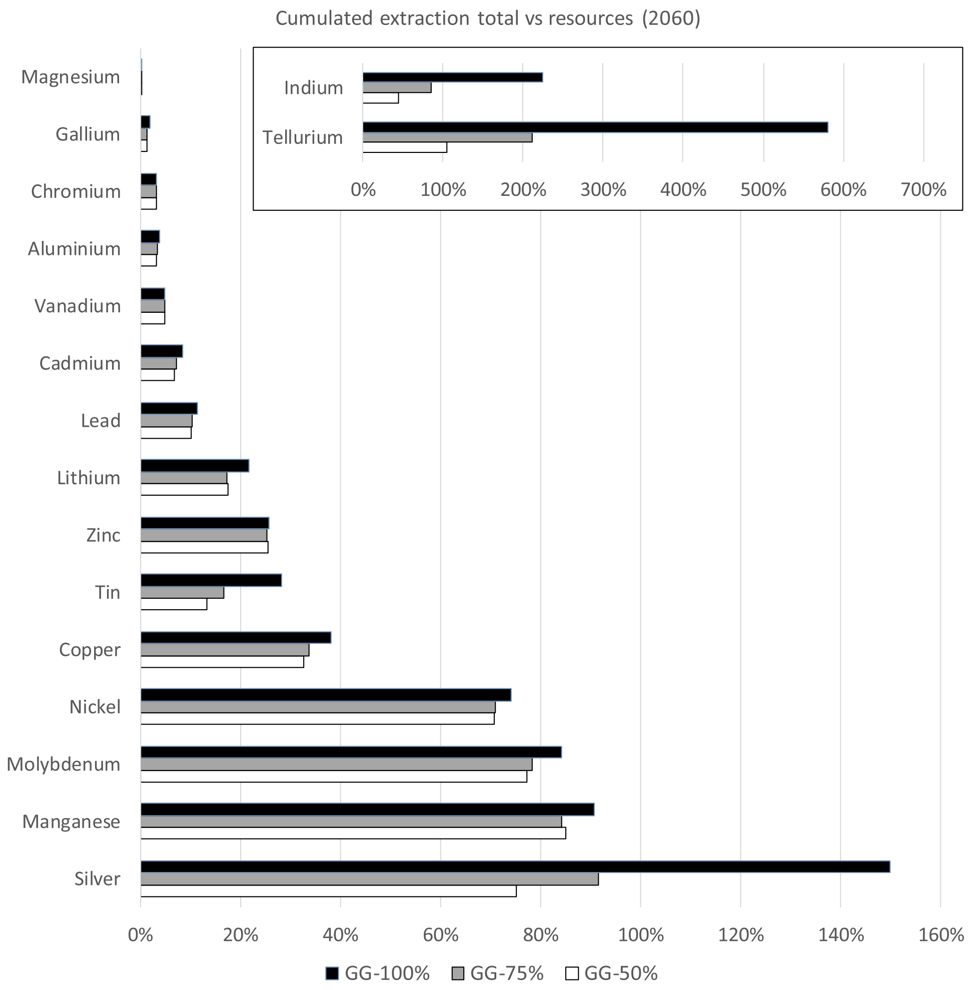

Fig. B2. Cumulated extraction (2015–2060) of minerals for the total system vs current resources for the three scenarios GG-20%, GG-50% and GG-100%.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2019.100399.

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