Energy & Environmental Science

PAPER

View Article Online
View Journal | View Issue

Cite this: *Energy Environ. Sci.*, 2020, **13**, 986

MEDEAS: a new modeling framework integrating global biophysical and socioeconomic constraints†

Iñigo Capellán-Pérez, *[ab] Ignacio de Blas, [ab] Jaime Nieto, [ac] Carlos de Castro,[ad] Luis Javier Miguel, [ab] Óscar Carpintero, [ac] Margarita Mediavilla, [ab] Luis Fernando Lobejón, [ac] Noelia Ferreras-Alonso, [e] Paula Rodrigo,[a] Fernando Frechoso [a] and David Álvarez-Antelo [a]

A diversity of integrated assessment models (IAMs) coexists due to the different approaches developed to deal with the complex interactions, high uncertainties and knowledge gaps within the environment and human societies. This paper describes the open-source MEDEAS modeling framework, which has been developed with the aim of informing decision-making to achieve the transition to sustainable energy systems with a focus on biophysical, economic, social and technological restrictions and tackling some of the limitations identified in the current IAMs. MEDEAS models include the following relevant characteristics: representation of biophysical constraints to energy availability; modeling of the mineral and energy investments for the energy transition, allowing a dynamic assessment of the potential mineral scarcities and computation of the net energy available to society; consistent representation of climate change damages with climate assessments by natural scientists; integration of detailed sectoral economic structure (input–output analysis) within a system dynamics approach; energy shifts driven by physical scarcity; and a rich set of socioeconomic and environmental impact indicators. The potentialities and novel insights that this framework brings are illustrated by the simulation of four variants of current trends with the MEDEAS-world model: the consideration of alternative plausible assumptions and methods, combined with the feedback-rich structure of the model, reveal dynamics and implications absent in classical models. Our results suggest that the continuation of current trends will drive significant biophysical scarcities and impacts which will most likely derive in regionalization (priority to security concerns and trade barriers), conflict, and ultimately, a severe global crisis which may lead to the collapse of our modern civilization. Despite depicting a much more worrying future than conventional projections of current trends, we however believe it is a more realistic counterfactual scenario that will allow the design of improved alternative sustainable pathways in future work.

Received 14th August 2019,
Accepted 21st January 2020

DOI: 10.1039/c9ee02627d

rsc.li/ees

Broader context

By substantially degrading the natural life-support systems and processes that sustain our existence, we are jeopardizing the survival of our societies. Holistic frameworks are required to assess the urgent and radical changes needed to change track and achieve a sustainable future. This study describes the open-source MEDEAS integrated assessment modeling framework, which has been designed to facilitate the assessment of policies for the best possible energy transition path during the next decades, with a focus on biophysical, economic, social and technological restrictions. The potentialities and novel insights that this framework brings are illustrated by the simulation of four variants of the continuation of current trends with the MEDEAS-World model. The consideration of alternative plausible assumptions and methods, combined with the feedback-rich structure of the model, reveal dynamics and implications absent in classical models. Our results show that the continuation of current trends will derive in biophysical scarcities and impacts which will most likely derive in regionalization, conflict, and ultimately global crisis, leading to the collapse of our modern civilization. Despite depicting a much more worrying future than conventional projections of current trends, this scenario seems a more realistic counterfactual scenario that will allow the design of improved alternative sustainable pathways in future work.

[a] *Research Group on Energy, Economy and System Dynamics, Escuela de Ingenierías Industriales, University of Valladolid, Paseo del Cauce s/n, 47011 Valladolid, Spain. E-mail: inigo.capellan@uva.es*
[b] *Department of Systems Engineering and Automatic Control, Escuela de Ingenierías Industriales, University of Valladolid, Paseo del Cauce s/n, 47011 Valladolid, Spain*
[c] *Department of Applied Economics, University of Valladolid, Av. Valle Esgueva 6, Spain*
[d] *Department of Applied Physics, Escuela de Arquitectura, University of Valladolid, Av Salamanca, 18, 47014, Valladolid, Spain*
[e] *CARTIF Foundation, Parque Tecnológico de Boecillo, Boecillo, Valladolid, 47151, Spain*

† *Electronic supplementary information (ESI) available. See DOI: 10.1039/c9ee02627d*

1. Introduction

The continuous increase of material and energy use is driving some of the key biophysical processes of the biosphere near – and in some cases over – the planetary boundaries.[1] References to potential non-linearities, thresholds and tipping-points of the biosphere have become common in the literature.[2–4] As humans, we critically depend on natural life-support systems and processes to sustain our own existence; by substantially altering and degrading them, we are risking the continuity of our societies as we now know them.[5–7] Hence, holistic frameworks and methodologies are required to assess the urgent, radical changes needed to enable human societies to achieve a sustainable future.

In this context, environmental integrated assessment modeling stands among the most practical scientific approaches. It refers to any type of analysis that seeks to integrate multiple disciplines and dimensions aiming to capture interactions between human and natural systems – which tend to be complex, dynamic and highly non-linear-, with the goal of providing useful information for policy making. Integrated Assessment Models (IAMs) (or energy–economy–environment (E3) models), are computer programs that link an array of component models based on mathematical representations of information from various disciplines. A great diversity of environmental IAMs exists due to the different approaches used by modelers striving to capture the complex interactions and high uncertainties involved in the environment/economy/society interface, with the dominance of IAMs focused on climate change research.[8–12]

In fact, dozens, if not hundreds, of IAMs have been developed in the last few decades since the pioneer World3 was developed in the early 1970s.[13,14] Despite great advances achieved in the field over the years,[8,10] most IAMs (and especially those more policy-influential), share a core set of common assumptions whose validity is being disputed in the scientific discussion. First, IAMs are generally characterized by a rather sequential structure with limited feedbacks among the represented subsystems. The interconnectivity of modules has likely being constrained by the historical development of most IAMs through linkage of existing modules which were not originally designed for being interlinked.[15] For example, natural science models must respect the laws of thermodynamics, while economic models often do not. Also, the discrepancy between the natural scientists' understanding of ecological feedbacks and the representations of environmental damage found in IAMs (if any) is especially relevant for the case of climate change impacts. Most IAMs fail to capture the "potentially irreversible threat to human societies and the planet" stated, for example, in the Paris Agreement.[4,9,16–21] Second, a lack of plurality in the methods to represent the economic dimension has been detected in the literature, dominated by assumptions of conventional general or partial equilibrium through optimization methods, perfect factor substitutability, as well as the widespread use of prices as indicators of scarcity. These simplifications fail to capture the relevance of sector complementarities within the economic structure, the socioeconomic system dynamics and the role of macroeconomic policies for sustainability governance.[22–28] Third, the abundance of both fossil fuels and renewable energy sources is a default assumption in most of the prominent IAMs used for climate policy analysis; hence, future energy transitions are thus largely modeled as demand-driven transformations only constrained by available monetary investments.[8,29,30] However, this assumption is disputed by studies in the literature showing that fossil fuels' extraction might face significant constraints in the next few decades related with increasing geological restrictions as the quality of the resource decreases.[30–32] Furthermore, a branch of literature is also showing that the replacement of fossil fuels in the current socioeconomic system by the large scale deployment of RES faces serious challenges in relation to biophysical factors such as intermittency or mineral and land requirements.[33–41] Fourth, most IAMs disregard the implications that the future energy investments required to achieve the transition to renewables may have for the system.[42–46] In fact, a favorable energy return on energy invested (EROI) (energy surplus) is a critical aspect of the viability of societies and has been associated with such fields as biology or anthropology as a key driver of increasing complexity and evolution for plants, animals and humans.[47–49] Finally, Fifth, (the lack of) transparency has been highlighted as being an issue in the field of IAMs critically affecting credibility and robustness of the results disseminated.[11,50,51]

This study is dedicated to the description of the MEDEAS modeling framework which has been designed with the aim of facilitating the assessment of policies to lead to the best possible energy transition path during the next few decades, with a focus on biophysical, economic, social and technological restrictions and tackling the aforementioned limitations in the current state-of-the art of IAMs. MEDEAS models have been developed within the homonymous project (Modeling Energy System Development under Environmental and Socioeconomic constraints),‡ whose main aim is to provide policy makers and stakeholders with new modeling tools to better assess the impacts and limitations of the EU energy production/consumption system transition to a low-carbon sustainable socio-economy. The MEDEAS models focus on the analysis of strategic, long-term outcomes of the human–nature interface, and have been designed applying system dynamics, which facilitates the integration of knowledge from different perspectives and disciplines, as well as feedbacks from the different subsystems. These models are open-source and can therefore be used by scientists, stakeholders and policy makers. Models at three different geographical aggregated scales have been developed: global, EU and country-level. Given that these geographical scales share a common modeling approach, for the sake of simplicity, in this paper we focus on the global model version. The simulation of a business-as-usual (BAU) scenario within the global MEDEAS model (MEDEAS-World) activating/deactivating some key functionalities shows the potentialities and novel insights that this framework brings when simulating future sustainability pathways.

‡ MEDEAS project webpage: https://www.medeas.eu/.

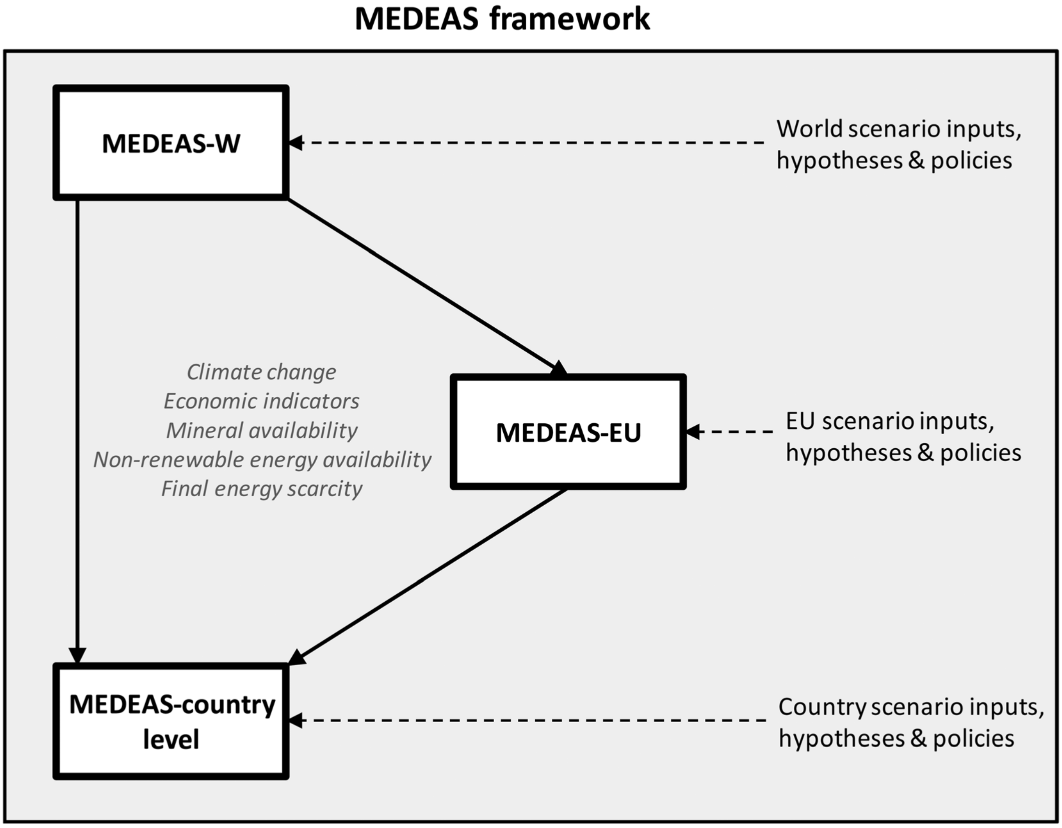

Fig. 1 One-way integration of different geographical scale models in MEDEAS framework. MEDEAS-W is the parent model of MEDEAS-EU, while the MEDEAS-country levels models have 2 parent models: both W and EU. The direction of the arrows represents outputs from the parents' models which feed the child models.

The paper is structured as follows: Section 2 describes the material and methods, Section 3 shows the simulation results of the 4 selected scenario cases, Section 4 discusses the obtained results and the novel insights of the proposed novel framework, and 5 concludes.

2. Material and methods

This section describes the main methods and assumptions applied to build the MEDEAS framework.

2.1. Overview of MEDEAS modeling framework

MEDEAS is a set of policy-simulation dynamic-recursive models sharing the same conceptual modeling approach which have been designed applying system dynamics by the Group of Energy, Economy and System Dynamics of the University of Valladolid (Spain). The models typically run from 1995 to 2060, although the simulation horizon may be extended to 2100 when focusing on long-term strategic sustainability analyses. Models at three different geographical aggregated scales have been developed: global (MEDEAS-W),[52] European Union (MEDEAS-EU)[53] and country-level for Austria and Bulgaria (MEDEAS-AUT and MEDEAS-BGR, respectively).§ [54] For the sake of simplicity, their integration is sequential (one-way): the parent models (W, EU) provide inputs for the child models (EU, country-model), which however do not affect the parent models. This assumption is taken considering that, due to the significantly smaller relative size of the EU and individual countries (AUT and BGR) with respect to the W and EU, respectively, the variation in the variables of the child models has a negligible impact on the variation of the variables of the parent models (see Fig. 1). Hence, economic indicators, non-renewable energy and mineral availability, as well as final energy scarcity from the higher geographical scale models, affect the lower geographical scale models. The simulation of each geographical model requires the outputs from the parent model(s) and the definition and quantification of its own scenario (including hypotheses and policies), all in an internally consistent way. The regional-scale models (EU and country-level) were adapted to include a representation of trade (at both final goods/services and primary sources of energy level) with the rest of the world combining a multiregional IOT structure with exogenous assumptions. Also, only the global model includes a carbon

§ MEDEAS models have been developed in system dynamics software Vensim DSS for Windows Version 6.4E (×32) and thereafter translated to Python. The latest versions of both Vensim and Python codes are freely available at: https://www.medeas.eu/model/medeas-model. Future updates of the models will be available at: http://geeds.eu/.

and climate cycle, regional models receiving the global average surface temperature increase under the simulated scenario as an exogenous input. The validation of the models has been carried out following several of the usual validation procedures of models in system dynamics[57,58] (uncertainty, sensitivity, robustness and stability analyses).[55,56] The historical data, although the available series are short, has been used for a first validation, and the results have been also compared with other models.[59]

MEDEAS models are structured in nine main modules: economy, energy demand, energy availability, energy infrastructures and EROI, minerals, land-use, water, climate/emissions, and social and environmental impact indicators. Fig. 2 shows the conceptual schematic overview of the global-aggregated scale MEDEAS-W, including the main relationships between the different modules. The main characteristics of each module are:

• Economy: the economy is modeled assuming non-clearing markets (*i.e.*, not forcing general equilibrium), demand-led growth and sector complementarity. 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 sectors (see ESI†) and 4 components of final demand.[60]

• 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 and physical scarcity.

• Energy availability: this module includes the potential and availability of RES 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.[61–63] In total, 25 energy sources and technologies, and 5 final energies are considered (electricity, heat, solids, gases and liquids), with large technological disaggregation. The modeling of energy availability is mainly based on the previous model WoLiM.[64] The intermittency of RES is considered in the framework, computing endogenous levels of overcapacities, storage and new electrical grids, depending on the penetration of variable RES technologies.

• Energy infrastructures & EROI: this module represents the capacities for generating electricity and heat, considering planning and construction delays. The energy investments for RES to produce electricity are endogenously and dynamically modeled, which allows the Energy Return on Energy Investment (EROI) of individual technologies and the EROI of the whole energy system to be computed. The energy demand is affected by the variation of the EROI of the system. Transportation is modeled 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, including those required for the construction, operation and maintenance of alternative energy technologies. Recycling policies are available.

• Land-use: this module mainly accounts for the additional land requirements of RES.

• Water: this module projects water use by type (blue, green and gray) by economic sector and for households.

• Climate/emissions: the global model computes the climate change levels due to the greenhouse gas (GHG) emissions generated by human societies (non-CO_2 emissions are exogenously set, taking RCP scenarios as reference 65). The carbon and climate cycle is adapted from C-ROADS.[66,67] This module includes a damage function which translates increasing climate change levels into damages to human systems. In regional models, domestic GHGs are computed and climate damages are dependent on the global average surface temperature's change from the associated global model scenario.

• Social and environmental impacts: this module translates the "biophysical" results of the simulations into metrics related to social and environmental impacts. The objective of this module is to contextualize the implications for human societies in terms of well-being and environmental impacts for each simulation.

The modules have different levels of development, being the economy, climate and those related to energy the ones most detailed. Minerals, land-use and water modules are more stylized representations focused to compute social and environmental Impacts which however do not feedback to the rest of the system (see Fig. 2).

MEDEAS models dynamically operate as follows. For each period, a sectoral economic demand is estimated from exogenous pathways of expected Gross Domestic Product per capita (GDPpc), population and income distribution. The final energy demand required to fulfill production is obtained using hybrid (energy–economy) input–output analysis, combining monetary output and energy intensities by type of final energy. The final energy supply computed within the energy availability and energy infrastructures and EROI modules may satisfy (or not) the required demand. In case of energy scarcity of any final energy type, two phenomena occur simultaneously: (1) final energy replacement to shift towards more abundant final energy types, and (2) adaptation of the economic production to the available energy. The materials required by the economy with emphasis on those required by alternative green technologies are estimated, which allows eventual future mineral bottlenecks to be assessed. However, for the sake of simplicity, mineral availability does not constrain economic output in the current model versions. The new energy infrastructures require energy investments, whose computation allows us to estimate the variation of the EROI of the system, which in turn affects the final energy demand. The climate module computes the GHG emissions associated to the resulting energy mix (complemented by exogenous pathways for non-energy emissions), whose accumulation leads to a certain level of climate change, which in turn feeds back to the economy affecting final demand. Additional land and water requirements are accounted for. Finally, a set of social and environmental impacts is computed. The simulation of regional models requires exogenous inputs provided by the parent models, as well as defining assumptions on multiregional monetary and energy trade.

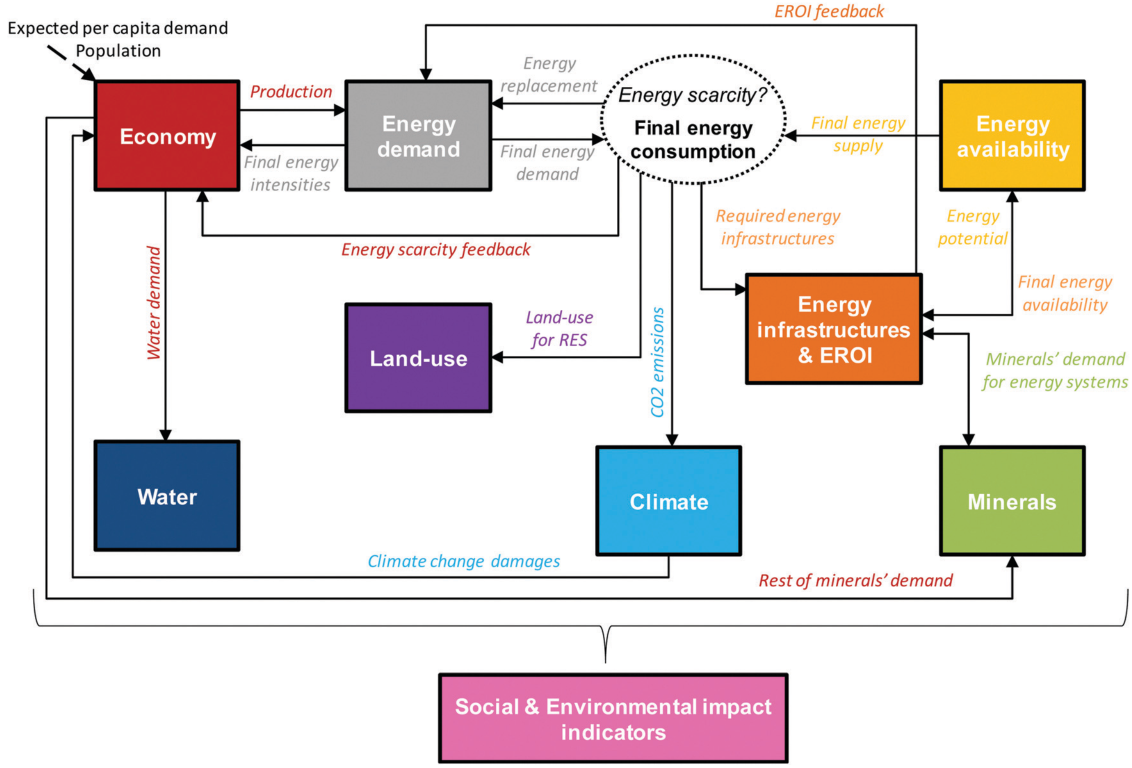

Fig. 2 MEDEAS-world model schematic overview. The main variables connecting the different modules (represented by colored rectangles) are represented in italics and by solid arrows. The dashed arrow represents the exogenous driver inputs. EROI: energy return on energy investment. RES: renewable energy sources. Source: adaptation from Capellán-Pérez *et al.*[52]

The remainder of the section focuses on the description of the main modules of MEDEAS-W.

2.2. Description of MEDEAS-world model

This section includes a synthetic description of the methodology applied to model the main modules of the MEDEAS modeling framework and its implementation in MEDEAS-W. At the end of each subsection, a footnote indicates a reference describing in detail each submodule. Full model equations and parameters are freely available in https://www.medeas.eu/model/medeas-model through the Python open-source code and the inputs file. The latter includes all parameters and provides a friendly interface for simulation scenarios. Hence, any user can perform simulations with the standard or modified structure and parametrization of the models.

2.2.1. Economy. The MEDEAS Economy module is framed in ecological economics principles, *i.e.*, assuming that the socioeconomic system is constrained by the environment and, therefore, subject to its biophysical boundaries,[23,68–71] aiming to overcome the underestimation – or even neglect – of biophysical constraints in most IAMs. By integrating hybrid (energy–economy) input–output analysis (IOA) and system dynamics, our approach is able to capture sectorial and structural conditions and limiting factors in energy transition scenarios. The Economy module represents the interdependencies between the economy and the environment through the energy and climate feedbacks; hence building bridges between ecological economics and post-Keynesian theoretical frameworks (demand-led growth affected by income distribution, adjustments *via* quantities, *etc.*), which are two of the main concerns of ecological macroeconomics. The ability to manage post-growth economies will be the object of further work.[24,72]

Fig. 3 shows the schematic overview of the Economy module of the MEDEAS framework. The production of goods and services is determined by the variation over time of the aggregate demand. At the beginning of any period, the variation of final demand based on population and GDPpc change, together with income distribution scenarios, using labor and capital share over GDP, allows the expected GDP to be set, as well as the expected profits and the expected total wage bill. The final demand function enables the estimation of the monetary demand by component of final demand for each sector (see eqn (1) and ESI†). Household consumption (hh) and Gross Fixed Capital Formation (gfcf) are estimated with behavioral equations based on panel data regressions, while Government expenditures (ge) and changes in inventories (invent) remain as a constant share of the sectoral final demand. Total final demand by sector (fd_i) is thus the sum of each institutional sector's demand (eqn (1)).

$$fd_i = hh_i + gfcf_i + ge_i + invent_i; \quad i = \in 1,\ldots,35 \text{ sectors} \tag{1}$$

The variation in expected demand triggers expected sectoral production requirements determined by the IOA. Final energy demand by type is computed through sectoral final energy

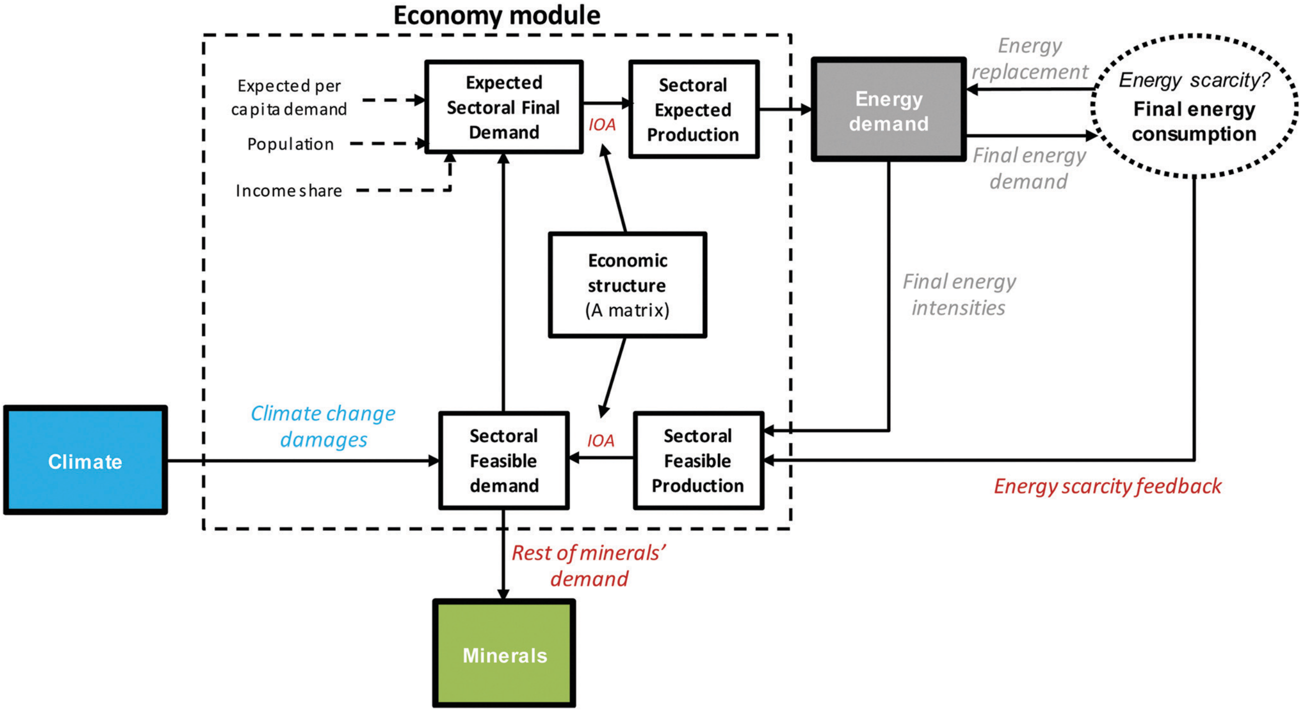

Fig. 3 Schematic overview of the Economy module of the MEDEAS framework. The dashed arrow represents the exogenous driver inputs. IOA: input–output analysis. Source: own work.

intensities (see Section 2.2.2). Finally, the feasible monetary final demand (which matches GDP at world level) adapts to the final energy availability determined in the Energy module (see Section 2.2.3).

Households demand (hh) depends (eqn (2)) on its main source of income, wages, *i.e.* labour compensation (Lab). Investment, or gross fixed capital formation (gfcf), is determined (eqn (3)) by the expected profits, *i.e.* capital compensation (Cap). β_2 coefficients in both equations were estimated through panel data regressions which proved consistent and well-fitted. β_{1i} coefficients allow for considering the individual (each sector) effects. Interest rates were considered also as an explanatory variable of investment but were found not significant:

$$\ln(\mathrm{hh}_i) = \beta_0 + \beta_{1i}\mathrm{Sec}_i + \beta_2\ln(\mathrm{Lab}) \quad (2)$$

$$\ln(\mathrm{gfcf}_i) = \beta_0 + \beta_{1i}\mathrm{Sec}_i + \beta_2\ln(\mathrm{Cap}) \quad (3)$$

with subscript 'i' ∈ 1,...,35 being the sectors' index, a constant (β_0) and an intercept (β_{1i}) depending on the sector (Sec_i) intercept, and β_2 measures their effect on final demand.

Thereafter, IOA is applied to compute the sectoral production x_i required to fulfill the expected demand. IOA is based on the standard accountability identities whereby production equals intermediate and final demand. In this method, **A** is the squared technical coefficients matrix representing the combination of inputs required to produce the output (**x**), and thus **A**·**x** amounts to the intermediate monetary final demand (**fd**). Therefore, $\mathbf{x} = \mathbf{A}\cdot\mathbf{x} + \mathbf{fd}$ and thus, solving for $\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\cdot\mathbf{fd}$, and renaming the first component as the so-called Leontief Matrix **L**, $\mathbf{x} = \mathbf{L}\cdot\mathbf{fd}$.¶[73] The Leontief matrix **L** allows the model to estimate both direct and indirect production carriers of final monetary demand, measuring the production sensitivity to final monetary demand. See Nieto *et al.*[72] for the analysis and discussion of different economic structure scenarios by setting a target **A** matrix to which the current one gradually evolves.

The estimation of the final energy demand (fed) in MEDEAS is performed through a general method based on projecting energy intensities by the final energy k (solids, liquids, gases, electricity and heat) (see Section 2.2.2, although bottom-up modelling is also possible, see Section 2.2.6). Thus, by multiplying the 35 sectors' energy intensities, broken down by final energy type (e_{ik}, see eqn (4)) with the sectoral production x_i, and adding the component of households obtained as their energy intensity (e_hh_k, see eqn (5)) multiplied by its final consumption hh, we obtain the total final energy demand by final energy tfed_k required to produce the economic output.

$$e_{ik} = \frac{\mathrm{fed}_{ik}}{x_i} \quad (4)$$

$$e\_\mathrm{hh}_k = \frac{\mathrm{fed\_hh}_k}{\mathrm{hh}} \quad (5)$$

In the event that the final energy supplied by the energy system for any final energy (tfes_k) is lower than demanded (tfed_k), a shortage coefficient ε_k is calculated (see eqn (6)). The feasible

¶ Boldface has been used to note matrices according to matrix notation. Nevertheless, subsequent equations are referenced to their index components.

sectoral production (x_i^{F}) is estimated with the most limiting final energy, while also accounting for the sectoral energy intensities (eqn (7)). The by-default model version considers that all the sectors are equally affected by the energy shortage, although this specification can be changed to assume response heterogeneity between sectors. Although the physical scarcity spurs progressive inter-final energy replacements through the system (see Section 2.2.2), in the short-run, substitution rigidities prevent immediate adaptation. The assumption of the economy adapting to the most limiting final energy follows the ecosystemic analogy (Liebig's law of the minimum) that growth is dictated not by total resources available, but by the scarcest resource. Its validity is justified by the high sensitivity of the world economy to key energy resources, notably oil (>95% of liquids historically), as demonstrated in the successive oil crises (1973, 1979, 2008).[74,75]

$$\varepsilon_k = \frac{\mathrm{tfes}_k}{\mathrm{tfed}_k}; \quad 0 \le \varepsilon_k \le 1; \quad k{:}1,\ldots,5 \tag{6}$$

$$x_i^{\mathrm{F}} = \min_{k:1,\ldots,5}\left(x_{ik}^{\mathrm{F}}\right) = \min_{k:1,\ldots,5}\left(\frac{\mathrm{fed}_{ik}^{\mathrm{F}}}{e_{ik}}\right) = \min_{k:1,\ldots,5}\left(\frac{\mathrm{fed}_{ik}^{\mathrm{R}}\cdot\varepsilon_k}{e_{ik}}\right) \tag{7}$$

where $\mathrm{fed}_{ik}^{\mathrm{R}}$ is the final energy demand required by sector and type of final energy. In the absence of final energy scarcity: $\mathrm{fes}_k = \mathrm{fed}_k \,\forall\, k \rightarrow \varepsilon_k = 1 \,\forall\, k$. Therefore, all the expected production is achieved.‖

2.2.2. **Energy demand.** Given the detailed sectoral disaggregation stemming from the IO structure, a novel method based on the top-down projection of the variation over time of sectoral final energy intensities has been developed to estimate the sectoral and households' final energy demands.[76] Energy intensity expresses the ratio between the energy used in a process and its economic output, and it is also often used as a measure of energy efficiency.[77]

As mentioned above (see Section 2.2.1), the MEDEAS framework considers 5 types of final energies (solids, liquids, gases, electricity and heat) and 35 economic sectors, which allows us to calculate 35 × 5 sectoral energy intensities e_{ik} and 5 energy intensities associated to households consumption e_hh_k. Hence, a total of 180 final energy intensities are handled in the MEDEAS framework. Except for inland transport sectors, which follow a bottom-up modeling (see Section 2.2.6) which could be eventually expanded to other sectors, the variation over time of each of the sectoral and households' final energy intensities is modeled in a top-down approach.

The starting point for modeling the dynamic behavior of final energy intensities is the available historical data, taking as reference the data from the WIOD database environmental accounts (1995–2009)[78] and complemented with the IEA balances.[79] In fact, energy intensities have generally declined over the last few decades.[80–82] The baseline trends assume variation rates of final energy efficiencies linked to historical technological change and economic growth,[77] and are based on the model proposed by Schenk and Moll[83] to explain the historical trend in energy intensity, considering biophysical and thermo-dynamical limits in the substitution of inputs.

The final energy intensities are assumed to change with reference to the baseline trends due to two factors:

(1) The variation in the energy intensity due to the improvement in energy efficiency, associated with the technology used in the consumption of each sector and type of final energy ($\Delta e_{ik}^{\mathrm{eff}}$).

(2) The variation in energy intensity due to the substitution of one type of final energy by another ($\Delta e_{ik}^{\mathrm{sub}}$). In this case, the type of energy that is replaced decreases its final energy intensity and the type of energy that replaces the previous one increases its final energy intensity.

The variations of the sectoral final energy intensities are assumed to be driven by two main factors (see eqn (8) and (9)):

(a) Market factors related to the scarcity of each type of energy. The scarcity of a type of energy can lead to greater efforts to increase energy savings and improve efficiency, as well as the substitution of that type of energy by more abundant ones. Indicators of physical scarcity have been specifically developed to represent physical supply-demand imbalances. Market factors are modeled through the perception of final energy scarcity (PS_k).

(b) Sociopolitical factors. Some policy measures, such as climate change mitigation policies, are promoting a greater effort in energy efficiency and fostering the substitution of fossil fuels.

$$\Delta e_{ik}^{\mathrm{eff}} = (\mathrm{PS}_k + \text{effects of policies}) \times \mathrm{Max}_{ik}^{\mathrm{eff}} \tag{8}$$

$$\Delta e_{ik}^{\mathrm{sub}} = (\mathrm{PS}_k + \text{effects of policies}) \times \mathrm{Max}_{ik}^{\mathrm{sub}} \tag{9}$$

An estimate of the maximum variations ($\mathrm{Max}_{ik}^{\mathrm{eff}}$ and $\mathrm{Max}_{ik}^{\mathrm{sub}}$) of the energy intensities has been obtained through a statistical analysis based on the historic data from WIOD.[84] An analogous approach has been applied to modeling the final energy demand of households' consumption.

The perception of scarcity of each type of final energy is dynamically estimated considering the eventual gap between supply and demand for each type of final energy ε_k. How to measure the scarcity or abundance of natural resources has been a controversial issue in economics for a long time.[85] The mainstream approach considering prices as a reliable indicator of scarcity of natural resources has been criticized, given its theoretical and empirical weaknesses. Energy and mineral prices are subject to multiple influences (institutional framework, oligopolistic market structure, *etc.*), which prevent perfect competition from happening in both the short and long-term.[26,86] Moreover, given the inertia and rigidities in the productive processes highly dependent on natural resources, important adjustments in the economic system are produced with quantity changes (instead of prices), as post-Keynesian approaches have highlighted.[25] Thus, MEDEAS applies an alternative ''biophysical'' perspective to model inter-final energy substitution, which takes into account dynamically the extraction of natural resources and their physical

‖ For a full description and technical parameters of the Economy module in MEDEAS-W see Nieto *et al.*[72]

scarcity (eqn (10)).[61,87,88]

$$\text{Scarcity}_k = \frac{\text{fed}_k - \text{fes}_k}{\text{fed}_k} \tag{10}$$

The perception of scarcity increases cumulatively with annual shortages and gradually decreases in the absence of annual shortages. The calibration of this variable has been performed with two parameters: the sensitivity of economic agents to scarcity (SS, differentiating between households and sectors) and the time to forget the perception of scarcity (FF) (eqn (11)).**

$$\text{PS}_k(t) = \text{scarcity}_k \times \text{SS} + \text{PS}_k(t-1)/\text{FF} \tag{11}$$

2.2.3. **Energy availability.** MEDEAS has a large disaggregation in the representation of energy sources and technologies. Table 1 shows the modeled 25 energy sources and technologies, and the 5 final energy categories.

Oil, natural gas, coal and uranium are the main non-renewable energy (NRE) resources considered in MEDEAS. Oil and natural gas are disaggregated between conventional and unconventional resources, distinction especially relevant to account for their different GHG emission factors. The availability of non-renewable energy resources in MEDEAS depends upon two constraints: stock (available resource in the ground) and flow (extraction rate of this resource). In fact, the constrained flow rates from deposits to consumers have been shown to be a more relevant limiting factor to follow demand than the remaining resource *in situ*. Technology can help regulate the extraction rate, but the latter is ultimately bound by geological-physical constraints.[61–63,89]

In order to consider the future availability of fossil fuels in the model, we performed a literature review of studies providing depletion curves over time, taking into account both stock and flow limit.[63,90–104] These curves represent extraction levels compatible with geological constraints as a function of time. Depletion curves, rather than predictions, represent maximum extraction profiles for a fraction of the resource base estimated to be economically extractable in the future considering geological constraints: the actual rate of resource consumption might be affected by such variables as geopolitics, economic conditions and technology development. Given that demand is endogenously modeled for each resource, these depletion curves are transformed so as to be incorporated in the dynamic model, being converted into maximum production curves as a function of remaining resources (see Fig. 4 and Appendix B in Capellán-Pérez *et al.*,[52] for details). The model user is free to select any depletion curve, introduce a new one, or even assume that no relevant constraints will affect the supply of any of the NRE resources in the simulation period.

Nine types of RES for electricity generation are modeled: hydro, solar PV, solar CSP, onshore wind, offshore wind, geothermal, biomass, oceanic and biogas; while for heat 4 sources are considered: solar, biomass, geothermal and biogas.

** For a full description and technical parameters of the energy intensities modeling in MEDEAS see de Blas *et al.*[84]

Table 1 Primary energy sources and technologies modeled in MEDEAS classified as non-renewable (NRE) and renewable (RES), and the corresponding final energy categories

MEDEAS final energy category	NRE/RES	Primary sources of energy and technologies modeled in MEDEAS
Solids	NRE	Coal Peat Waste
	RES	Charcoal Biomass (modern) Biomass (traditional)
Liquids	NRE	Conventional oil Unconventional oil CTL (Coal to Liquids) GTL (Gas to Liquids)
	RES	Biomass (biofuels)
Gases	NRE	Conventional natural gas Unconventional natural gas
	RES	Biogas
Electricity	NRE	Natural gas Oil Coal Uranium Waste
	RES	Hydroelectricity Geothermal power Biomass Oceanic (Wave, tidal, OTEC) Onshore wind Offshore wind Solar PV Solar CSP Biogas
Heat[a]	NRE	Coal Natural gas Oil Nuclear (cogeneration) Waste
	RES	Geothermal Solar thermal Biomass Biogas

[a] MEDEAS does not differentiate between different temperature levels for heat.

Bioenergy is modeled in four main categories: (1) traditional biomass, (2) modern solid biomass for heat and electricity, (3) residues, and (4) dedicated crops in current croplands and in marginal lands (*i.e.*, land that was previously used for agriculture or pasture but that has been abandoned and not converted to forest or urban areas[106]) for biofuels. It is possible to activate the availability of third generation ligno-cellulosic fuels for a given year (see Capellán-Pérez *et al.*,[52] for details). Special attention is devoted to the land requirements of RES technologies (see Section 2.2.7), given that the transition to RES will intensify the competition for land globally.[38,107,108] In this sense, the potential of some RES is defined by the user as a function of the land assessed to be available in the future (solar on land, cropland for liquid biofuels and marginal lands), while for the rest of RES the potential is directly set in power terms by the user.

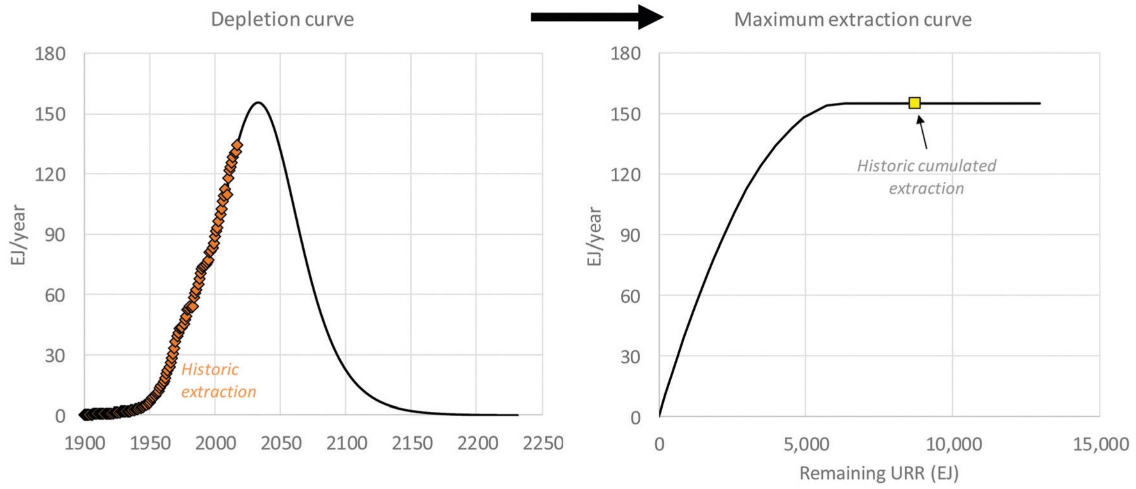

Fig. 4 Example of the transformation of a depletion curve (left) in maximum extraction curve (right) suppressing time dependence as a function of remaining ultimately recoverable resources (URR). The depletion curve as example is total natural gas from Laherrère.[105] Source: own work.

The selection of new alternative technologies still not competitive modeled in MEDEAS takes as reference the precautionary principle, which is the most robust approach in uncertainty contexts such as the one characterizing climate change and the sustainability crisis.[68] Two criteria have been applied:[52]

(1) Given the need for urgent action to stabilize climate and reverse current unsustainable trends, focus on those technologies that are currently available and proven to be commercial. In fact, it has been shown that new technologies and energy systems take several decades to diffuse through the economy.[109,110]

(2) Ensure that the net energy balance of the considered technologies is positive, *i.e.*, that the technology will be a "reasonable" net energy contributor to society. Although an energy system with EROI at the point of use <1–2 could still be used for some specific purposes, it would rather be an anecdotal technology; given the burden it would impose on the whole energy system (it would be an energy drain rather than a source).

In the light of these criteria, carbon capture and storage,[111,112] Negative Emission Technologies (NETs),[112–117] hydrogen, nuclear fast breeders and nuclear fusion are not included in the current MEDEAS framework.†† [118]

2.2.4. Minerals. The Minerals module in MEDEAS allows the potential effects that mineral depletion may exert on the future energy transition to be assessed and the EROI of a set of key alternative energy technologies (see Section 2.2.5) to be endogenously estimated. The demand of minerals in MEDEAS-W is split into 2 categories: (1) minerals demanded by 6 key alternative "green" technologies for the transition towards fully RES-based energy systems (solar PV, solar CSP, onshore wind, offshore wind, electric vehicle batteries and electric grids), and (2) minerals demanded by the rest of the economy.

This split is required to deal with the fact that data concerning mineral consumption globally are generally of low quality (lack of robust data and sectoral detail, *etc.*).[40,119] Given the lack of data on material demand associated to the WIOD sectors, a stylized approach was applied to estimate the future demand of minerals by the rest of the economy, assuming a linear dependence with GDP.[120] Historical data for the global GDP[121] and the extraction of minerals[122] for the period 1994–2015 were applied to estimate the parameters of the regressions, obtaining acceptable correlations in most cases.[46]

For each of the key "green" technologies, a representative technology was selected, taking into account the present and foreseen performance while avoiding those more likely to be affected by scarce minerals in the future.‡‡ Subsequently, a literature review was performed to identify the material intensity (kg MW^{-1}) of each representative technology, including those related to additional grid requirements, for a total of 58 materials, of which 19 are minerals (aluminum, cadmium, chromium, copper, gallium, indium, iron, lead, lithium, magnesium, manganese, molybdenum, nickel, silver, tellurium, tin, titanium, vanadium and zinc). Selection criteria were based on considering all relevant materials so as to accurately estimate the embodied energy for the EROI estimation (see Section 2.2.5), with potential critical minerals having already been identified in the literature,[40,127–130] as well as specific assessments.[52] A comprehensive literature review, complemented by our own estimations, was performed to collate the most robust and accurate data concerning material requirements for each technology. In the case of uncertainty about potential double accounting, material requirements were not included. Hence, these estimations can be considered conservative/optimistic.

†† For a full description and technical parameters and technology choice of the energy availability modeling in MEDEAS see Capellán-Pérez *et al.*[52]

‡‡ The selected representative technologies are the following: CSP with molten-salt storage without back-up, most efficient and used technology (back-up option is usually powered by non-renewable fuels such as natural gas);[123] fixed-tilt silicon PV (best EROI)[124] and subject to fewer mineral availability constraints (a weighted average is computed for some minerals taking into account the current share of PV sub-technologies such as thin-films);[34] 2 MW onshore wind turbines (currently the global average onshore wind turbine capacity is lower than 2 MW[125]); 3.6 MW offshore wind turbines taking as reference the current average size in Europe;[125] and $LiMn_2O_4$ electric vehicle batteries given that, although they are less efficient than other alternatives (*e.g.* $LiCoO_2$), the embodied energy for their fabrication is substantially lower.[126]

Given the existing uncertainties in future mineral availability,[131–133] MEDEAS compares the cumulated primary demand of minerals (after accounting for recycling rates) with the current estimated level of their geological availability (reserves and resources) for a qualitative detection of risks to the future mineral supply. Hence, potential mineral scarcity in the current model version is not feed-backed and does not affect the rest of the model, as is the case with energy (see Section 2.2.1) (*i.e.*, mineral supply is assumed to always fulfils demand).§§

2.2.5. Energy infrastructures and EROI of the system. MEDEAS focus on the representation of the infrastructures related with the generation of electricity and heat by RES such as wind farms, solar systems, additional power lines, *etc.*, while capacities are implicit for fossil fuel power plants. This choice is made for the sake of simplicity given that the energy transition will mainly consist on switching the later and enabling the former. RES-related infrastructures are represented as capacity stocks with a given lifetime, and are built according to the rate of investment of new capacity (exogenously set by the user), limited by the potential of the resource following fractional growth (logistic). The deployment of these infrastructures depends on factors such as the configuration of the mix (*i.e.*, intermittency management of variable RES) or the EROI of each technology. The intermittency of RES is considered in the framework, computing endogenous levels of overcapacities, storage and new electric grids, depending on the penetration of variable RES technologies (see Capellán-Pérez *et al.*,[46] for details). Physical supply-demand unbalances in the market drive inter-final energy shifts (see Section 2.2.2), while technologies producing the same final energy follow a merit-order-effect in which renewables have priority over fossil fuels. The inter-final energy shifts also drive substitutions at primary sources of energy level, subjected to technological and dynamic constraints.[84]

The net energy available, and not the primary one, is the relevant factor to society.[46–49] Acknowledging the difficulties of computing broad boundaries for the EROI,[124,134–137] a first, conservative step is taken that focuses on the dynamic computation of the EROI of the system from a standard ($\mathrm{EROI}^{\mathrm{st}}_{\mathrm{system}}$) approach. The standard approach includes the energy requirements to get energy (*e.g.*, build, operate and dismantle power plants) but omits those energy requirements to deliver energy to the point of use of society ($\mathrm{EROI}^{\mathrm{final}}$) as well as those energy requirements to build the machines and infrastructure required to construct the machines and infrastructure which allows to make the energy investments ($\mathrm{EROI}^{\mathrm{ext}}$). The dynamic $\mathrm{EROI}^{\mathrm{st}}_{\mathrm{system}}$ ¶¶ is defined here as the ratio over time between the final energy delivered to society and the energy investments associated to the up-front energy costs of variable RES power plants before they start to deliver energy, the energy investments associated to operation and maintenance as well for variability management during operation, and the dismantling costs at the end of the lifetime.‖‖ Given the data intensiveness of this method,[46] the focus is on variable RES given their much higher techno-sustainable potential comparing with dispatchable RES.[143,144] (see eqn (12) and Fig. 5). The resulting net energy is given by eqn (13):

$$\mathrm{EROI}^{\mathrm{st}}_{\mathrm{system}} = \frac{(1)}{(2)+(3)} \tag{12}$$

$$\text{Net energy} = \text{gross energy returned} \cdot \left(1 - \frac{1}{\mathrm{EROI}}\right) \tag{13}$$

Note that, in the literature, the $\mathrm{EROI}^{\mathrm{st}}$ of individual technologies is usually defined as (1)/(2) (final energy content) or (1)/(0) (primary energy content of the source).[123,136]

The following assumptions are taken to compute the $\mathrm{EROI}^{\mathrm{st}}_{\mathrm{system}}$:

• Dynamic and endogenous calculation of the $\mathrm{EROI}^{\mathrm{st}}$ of each RES variable technology for electricity generation computing the required energetic costs taking as a starting point the materials required in the construction, operation, maintenance and dismantling phases (see Section 2.2.3) and combining this data with the energy consumption per unit of material consumption from Life Cycle Analysis (LCA).[145] Estimates are derived from physical inputs and no indirect estimates based on associated economic costs are considered. For RES dispatchables for electricity generation, $\mathrm{EROI}^{\mathrm{st}}$ values over the lifetime from the literature are taken as reference for the sake of simplicity.

• The $\mathrm{EROI}^{\mathrm{st}}$ of non-renewable energy sources, as well as for renewables other than electricity generation is conservatively[146,147] assumed to be constant over time for the sake of simplicity.

• The energy requirements associated to the overcapacities, storage and construction of new electric grids related to the increasing penetration of variable RES technologies in the system are endogenously computed by the model.

In principle, we do expect technology improvements in the future, however we also foresee that there will be other relevant factors which in the medium term will tend to offset them as the RES progressively scale-up at large levels and gain substantial shares in the energy mix: (1) decreasing returns in the potential of renewables, *i.e.*, after best places are occupied it is necessary to move to more uneconomical sites,[148–150] phenomena which may be worsened by eventual land availability constraints in some cases; (2) the increase in energy requirements due to ore grade decrease of minerals with cumulated extraction;[151–153] (3) thermodynamical limits to the continuous reduction of energy investments (*e.g.* related with limits to

§§ For more details on the methodology and assumptions for the estimation of materials in MEDEAS, see Capellán-Pérez *et al.*[46]

¶¶ Note that dynamically accounting for energy magnitudes corresponds with power rather than to 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 of ''dynamic EROI'' more commonly used in the literature[75,138,139] (although other more recent works have coined new terms such as ''power return on energy invested'' (PROI)[136,140] or ''net external power ratio'' (NEPR)[141,142]). Still, it should be kept clear that the different nomenclature refers ultimately to the same concept.

‖‖ Note that there is a lack of standardization in the literature, and other works estimate the $\mathrm{EROI}^{\mathrm{st}}$ at the power plant instead rather than at the system level, use the energy delivered at the mouth-gate of the power plants rather than the one delivered at the final consumer, and do not incorporate the additional energy investments related with intermittency management.

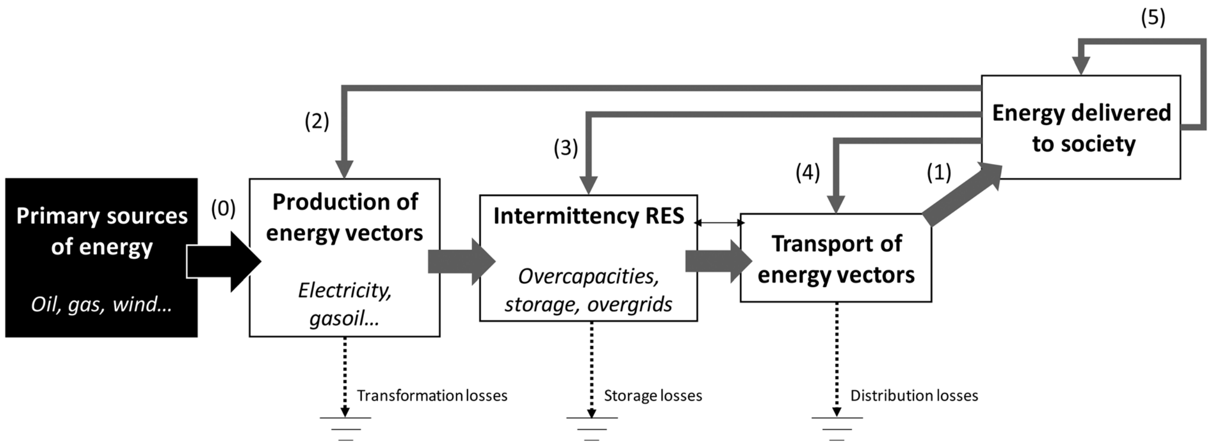

Fig. 5 Representation of the energetic metabolism of our society. Grey arrows refer to energy flows that are usable by human societies. The black arrow on the left-hand side (0) is a flux of materials with potential energy which can be transformed into usable energy. Dashed vertical arrows represent energy losses at each phase of the chain (transformation, storage and distribution losses). An exosomatic intermediary (arrows 2, 3, 4 and 5) is always required to transform the potential energy into useful exosomatic energy usable by society (1) (excluding non-energy uses) (size of arrows is not to scale). Source: Capellán-Pérez *et al.*[46]

substitution); (4) the scarcity of some minerals in the future may drive the shift to more abundant minerals which in turn are generally characterized by a lower performance (*e.g.*, replacement of Ag in solar PV[34]); and (5) thermodynamical limits from the side of generation, as for example the Benz law or the fact that there are absolute limits to the height of rotors for wind or the limits in the conversion from sunlight to electricity such as the Schokley–Queisser limit. Hence, the current performance parameters for RES technologies are taken as reference in the model as a first approximation and further work will be directed to model these opposed effects.

Summarizing, MEDEAS dynamically accounts for the $\mathrm{EROI}^{\mathrm{st}}$ of the system as shown in eqn (14):

$$\mathrm{EROI}(t)^{\mathrm{st}}_{\mathrm{system}} = \frac{\mathrm{TFEC}(t)}{g^{\mathrm{syst}}(t)\cdot\left(\mathrm{OEU}(t)+\mathrm{TFEI}(t)_{\mathrm{RES\,elec}}+\mathrm{TFEI}(t)_{\mathrm{storage\,elec}}\right)} \quad (14)$$

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

$\mathrm{TFEI}_{\mathrm{RES\,elec}}$: total final energy investments for renewable technologies of electricity generation.

$\mathrm{TFEI}_{\mathrm{storage\,elec}}$: total final energy investments for storage of electricity.

OEU: energy industry own-energy use (excepting for electric renewables to avoid double accounting).

g^{syst} = final to primary energy sources ratio (1)/(0) (see Fig. 5), which make possible to deal with the challenge of computing the EROI of the full energy system in a dynamic framework with a set of final energies.[46] $g^{\mathrm{techn}} = 1$ is defined for the computation of the EROI of each of the renewable technologies for the generation of electricity.

The variation of the EROI of the system would imply a variation in the energy intensity of the economic sectors linked to the generation, transformation and transport of energy, with implications for investments and available income to households. However, given the limitations of the WIOD sector categorization (*e.g.*, sector 17 ''Electricity, Gas and Water supply'', see ESI†), the effect of the variation of the EROI of the system is modeled instead as a variation of the total final energy required by the system in relation to a reference year (2015). Thus, a decrease (increase) of the EROI in relation to the reference year induces an increase (decrease) of the demand of total final energy. Hence, this approach does not capture the metabolic implications of the drop of the EROI of the system to very low levels.*** [154]

2.2.6. Transportation. Transportation is a key economic sector for most industrial processes and the means of trade. It is very dependent on liquid fuels (95%), notably oil (>92%).[79] This is why MEDEAS models Transportation in great detail, enabling the simulation of bottom-up transition policies based on the shift from liquid-fuel-based vehicles to other types of vehicles. These bottom-up policies are only applied to households and inland transportation. Alternative technologies for air and water transportation are not considered, since the use of other fuels than liquids in those sectors does not seem to be a realistic large-scale commercial option in the foreseen future.[155–159] For these sectors, the standard top-down energy intensity improvement is considered (as for the rest of the economic sectors in the model, see Section 2.2.2).

Two types of household vehicles are considered: four-wheelers and two-wheelers; and four types of inland transport vehicles: heavy, light cargo, buses and trains. Four types of energies are considered: liquids, hybrid, gas (only natural gas, since GLP is considered a liquid fuel) and electric (which includes battery electric cars and plug-in hybrids). The focus is on those vehicle types which seem more realistic to represent

*** For more details on the methodology and assumptions for the estimation of the EROI of the system in MEDEAS, see Capellán-Pérez *et al.*[46]

a significant share of the future transportation mix based on current knowledge about technical performance and foreseen limits. Hence, some of the combinations such as: motorbikes based on gas or hybrid, purely electric heavy trucks,[158–160] or hybrid and gas based trains have not been considered in this model version.

In this model version, we assume that the current patterns of mobility are maintained since cultural changes are far from conventional scenarios.[161–164] Hence, the total number of vehicles is determined by economic demand (see Section 2.2.1).

The user can set policy targets in terms of target shares of a type of vehicle in a given year. The model translates these into changes to the corresponding final energy intensities of the Households and the Inland Transportation WIOD sector.

The corresponding derivative of the energy intensity by type of final energy k (liquids, electricity, gases) can be expressed as a function of either total households' consumption (hh) or inland transport sector production ($x_{\text{inland transport}}$) and their respective energy demand fed_hh_k or $\text{fed}_{\text{inland transport},k}$ of transport uses, considering the change in the share of vehicles and the technical efficiencies. Eqn (15) shows the expression applied for households' liquids vehicles, describing the variation of eqn (5):

$$\begin{aligned}\frac{\mathrm{d}e\_\text{hh}_{\text{liq}}}{\mathrm{d}t} &= \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\text{fed\_hh}_{\text{liq}}}{\text{hh}}\right)\\ &= \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{H\cdot\%H_{\text{liq4w}}\cdot\text{use}_{\text{H4w}}\cdot\text{EF}_{\text{liq4w}}}{\text{hh}}\right)\\ &\quad+\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{H\cdot\%H_{\text{hyb4w}}\cdot\text{use}_{\text{H4w}}\cdot\text{EF}_{\text{hyb4w}}}{\text{hh}}\right)\\ &\quad+\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{H\cdot\%H_{\text{liq2w}}\cdot\text{use}_{\text{H2w}}\cdot\text{EF}_{\text{liq2w}}}{\text{hh}}\right)\end{aligned}\tag{15}$$

where H is the total number of household vehicles (2 and 4 wheelers), $\%H_{\text{liq4w}}$, $\%H_{\text{hyb4w}}$, $\%H_{\text{liq2w}}$ the share of liquid 4 wheelers, hybrid 4 wheelers and liquid 2 wheelers; use_{H4w}, use_{H2w} the average use of 4 wheel and 2 wheel vehicles in terms of km per year per vehicle, EF_{liq4w}, EF_{hyb4w}, EF_{liq2w} the technical efficiencies of vehicles expressed in energy per km.

Assuming the continuation of the current mobility patterns, the number and use of vehicles divided by households' demand can be assumed to be constant (however, the modeling framework can be extended to account for modal shifts and demand-management options, see de Blas *et al.*[165]). Therefore, we might define the constants $A1$ and $A2$ (computed for the year 2015) (eqn (16)):

$$\begin{aligned}A1 &= \left(\frac{H\cdot\text{use}_{\text{H4w}}\cdot\text{EF}_{\text{liq4w}}}{\text{hh}}\right)\\ A2 &= \left(\frac{H\cdot\text{use}_{\text{H2w}}\cdot\text{EF}_{\text{liq2w}}}{\text{hh}}\right)\end{aligned}\tag{16}$$

and express the variation of the intensity as (eqn (17)):

$$\begin{aligned}\frac{\mathrm{d}e\_\text{hh}_{\text{liq}}}{\mathrm{d}t} &= A1\frac{\mathrm{d}}{\mathrm{d}t}\%H_{\text{liq4w}} + A1\cdot\text{sr}_{\text{hyb}}\\ &\quad\times\frac{\mathrm{d}}{\mathrm{d}t}\%H_{\text{hyb4w}} + A2\cdot\frac{\mathrm{d}}{\mathrm{d}t}\%H_{\text{liq2w}}\end{aligned}\tag{17}$$

Technical efficiencies are relative to the efficiency of liquid vehicles using saving ratios (sr). The same approach is used for electricity and gas and for the Inland Transportation vehicles. The number of vehicles of each type and electric batteries required is also estimated, which allows to compute the associated mineral requirements.†††

2.2.7. Land-use. Land-use and land cover dynamics are highly complex given their dependence on a diversity of interlinked, and geographically very diverse, natural and human factors. Forthcoming climate change increases the challenge. In this sense, relatively few IAMs include a representation of this dimension, such as GCAM[166] or IMAGE.[167] Considering this and the scope of the MEDEAS project within which the present research has been performed, the MEDEAS land dimension focuses mainly on the land requirements of the RES energies, which have been found to be substantially higher than their fossil fuel counterparts.[38,107,108,168] The model computes the additional land requirements associated with the transition towards renewable energies, taking the power density levels of the different technologies and energies (biofuels, solar PV, solar CSP and hydroelectricity) as a starting point.[107] Liquid biofuels requiring land in MEDEAS are produced in cropland and marginal lands, considering improved land-use efficiencies for advanced ligno-cellulosic biofuels with relation to 2nd-current biofuels such as bioethanol and biodiesel. The model user selects, through literature review, the amount of both arable and marginal land available for biofuels in each scenario consistently with the tested storyline. Subsequently, the additional land requirements obtained for each scenario can then be compared with other magnitudes (*e.g.*, current arable, built-up land, *etc.*) in order to build risk indicators.‡‡‡

2.2.8. Water. Water is essential for human life and the preservation of ecosystem functions, and as such is acknowledged as a planetary boundary.[1,169] However, few IAMs integrate water in the analysis, among the exceptions stand GCAM[170] and IMAGE.[167] Its modeling is critically affected, as in the case of land-use, by the complexities of integrating a highly geographically dependent dimension. In MEDEAS, a macro perspective is taken by estimating the demand of water by type (blue, green and gray)§§§ by economic sector and for households using WIOD environmental accounts.[78,171] Water demand is thereafter compared with the available

††† For a full description and technical parameters of the modeling of transportation in MEDEAS, see Capellán-Pérez *et al.*[52]

‡‡‡ For more details on the land-use module in MEDEAS, see Capellán-Pérez *et al.*,[52] and de Blas Sanz *et al.*[53]

§§§ Blue water refers to the consumption of surface and ground water; green water is the volume of rainwater consumed, mainly in crop production; and gray water is the volume of freshwater required to assimilate the load of pollutants based on existing ambient water quality standards.

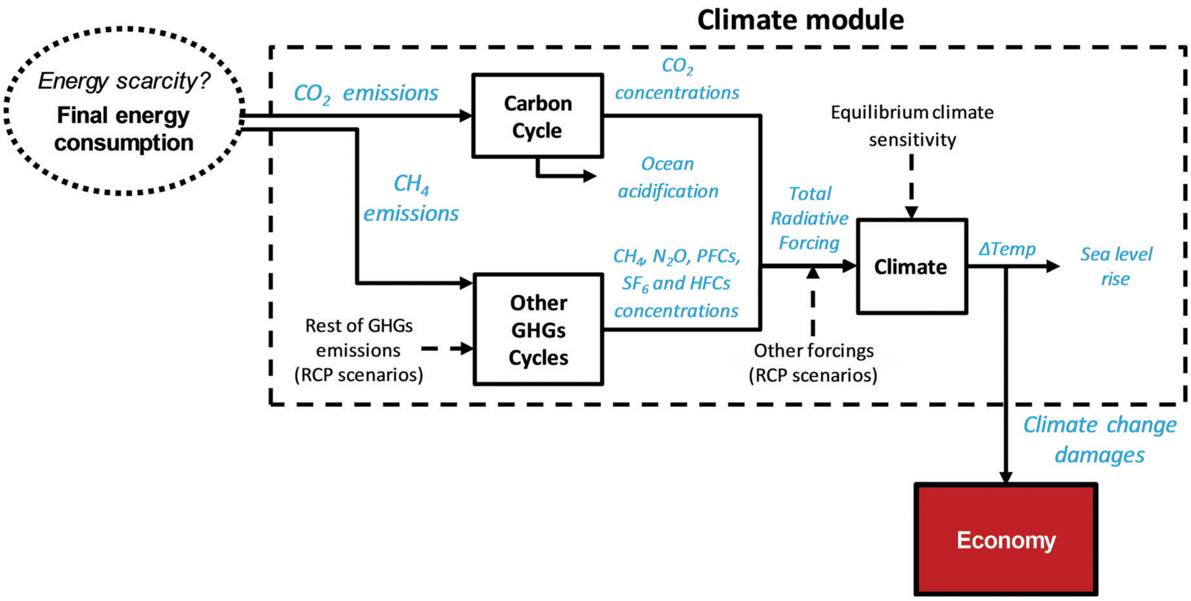

Fig. 6 Simplified structure of the Climate module in MEDEAS-W. The dashed arrow represents the exogenous driver inputs. Source: own elaboration.

resource as a means to assess the pressure level exerted on the resource; although, for the sake of simplicity, as for minerals and land-use, there is no feedback of eventual scarcities into the rest of the system.

2.2.9. Climate. The Climate module in MEDEAS-W is based on the climate model C-ROADS,[66] which is a state-of-the-art model able to run in MEDEAS computational time (*i.e.*, avoiding the complexity and long simulation times of Global Circulation Models[172]). The C-ROADS model is based on the works of Fiddaman,[173] Goudriaan and Ketner[174] and Oeschger *et al.*[175]

Fig. 6 represents the main elements of the Climate module in MEDEAS-W, which functions as follows: on the one hand, the anthropogenic CO_2 emissions, endogenously generated within the model due to energy consumption and land-use changes, enter the carbon cycle, estimating the level of CO_2 concentration in the atmosphere. The carbon cycle represents the dynamics between the carbon in the atmosphere, the biosphere (humus and biomass) and the ocean, including temperature feedbacks.

The emissions of the rest of the GHGs are mostly exogenous, except for CH_4, for which the share of its emissions associated to the extraction, distribution and combustion of natural gas is endogenously calculated, considering its whole lifetime.[176] The user can select the level of future emissions of the rest of the GHGs through the selection of their respective RCP scenario.[65] The other GHGs cycles (CH_4, N_2O, PFCs, SF_6 and HFCs) are also explicitly modeled in MEDEAS-W, including the mutual interactions, such as between CH_4 and N_2O.

The instantaneous warming of all GHGs (total radiative forcing) is aggregated through their respective radiative forcing coefficients, which allows the global-average temperature increase with relation to pre-industrial levels to be computed. The user can modify the equilibrium climate sensitivity, which is set by default to the standard value of 2.9 °C, in response to a doubling equivalent change in radiative forcing. Other climate impacts, such as ocean acidification and sea level change, are also calculated.

The modeling of climate change damages to human societies is a very challenging topic, given the complex uncertainties that pervade the coupled human–Earth system, the long time horizon of the problem, as well as the heterogeneous nature of climate impacts across regions, sectors and generations; additionally, there is no historical analogue for their assessment.[17,177] Global surface temperature has already increased around +1 °C over pre-industrial levels and scientific evidence is increasingly indicating that the political targets of +1.5/+2 °C set in Climate Summits, such as that reached in Paris in 2015,[178] do not represent a safe aspiration for the long-term sustainability of human societies.[4,179,180] On the other hand, the review of the literature shows that there is a large gap between natural scientists' understanding of climate impacts and their representation in IAMs, where temperature change is typically assumed to increase in business-as-usual scenarios between 4–5 °C by the end of the century, with negligible representation of the impacts and damages on humans and the biosphere.¶¶¶ [8,17–21]

In this context, a novel methodology to introduce climate damages in MEDEAS-W, based on the concept of damage function, has been specifically developed, incorporating novel insights and methods proposed in the discussion/debate

¶¶¶ The authors are aware that IAMs which do not include a damage function usually operate under the "cost-effectiveness" approach, *i.e.*, they focus on finding a system configuration which minimizes the costs of the transition.[8,181] However, by ignoring the costs of the non-action (already partially unavoidable), the results obtained under this method are, therefore, flawed. As an example, the investments required for the transition obtained in these IAMs are computed and communicated as mitigation costs.

around the integration of climate change impacts in standard cost-benefit IAMs, including:

• Consistent representation of climate change damages with climate assessments by natural scientists assured through the application of the top-down inductive approach[18,21,182] for the calibration of the damage function through informed-interpretation of ''dangerous climate change''.

• Climate impacts affect the drivers of growth (or growth rates) and not just the level of production.[17,18,20,21,177,183–185]

Two options are available in MEDEAS-W for the user: (1) an energy losses function which reduces the final energy consumption available for production after climate change impacts (dependent on the level of CO_2 concentrations), and (2) a monetary damage function which relates average global surface temperature change with the loss of GDPpc due to climate change damages. In both cases, the damage function is calibrated by applying an inductive method to assure consistency with climate change impact assessments. At current ''low'' climate change levels, the damages can be considered negligible, while at high concentrations/temperature increase, the damages are catastrophic. Non-linear functions are considered (logistic and parabolic, respectively) in order to represent the non-linearity between climate change and the related impacts. The user can also easily perform runs deactivating these damages and running the model without considering climate change impacts.‖‖‖‖

2.2.10. Social and environmental impact indicators. Given that well-being is intrinsically linked to a healthy environment, able to provision the so-called ''ecosystem services'',[5–7] the reporting of key environmental impact indicators is considered within social indicators. Translating the outputs of each scenario into a set of variables that provide information about its social dimension is a complex and delicate task, since, in fact, typical social dimensions such as education, health, culture, life expectancy, governance, *etc.*, depend on more dimensions than those modeled in MEDEAS, which mainly represents biophysical and monetary variables. Thus, the robust computation of indicators such as the Human Development Index (HDI) as well as the interactions with institutions and ideations of political power are further the scope of the current work.****

Acknowledging that welfare is a multidimensional feature which cannot be reduced to a single variable,[187] MEDEAS does not report a ''unique'' variable to measure welfare. Instead, the assessment of each scenario in social terms requires the concurrent analysis of a set of diverse variables from the different dimensions analyzed within the framework (see Table 2). With this complex perspective, trade-offs often arise between different dimensions. In particular, energy is a key variable of the MEDEAS framework which contains valuable information; in fact, an adequate energy supply has been identified as a key prerequisite for economic, cultural and social development in complex societies, especially at lower consumption levels,[188–192] and as such it has been included in the SDG7 to ''ensure access to affordable, reliable, sustainable and modern energy for all''.†††† [193]

‖‖‖‖ For a full description and technical parameters of the climate modeling in MEDEAS, see Capellán-Pérez *et al.*,[52] and for the modeling of climate change damages in MEDEAS-W, see Capellán-Pérez and de Castro.[186]

**** Even though MEDEAS only estimates 1 out of 3 of the components of the HDI (neither life expectancy at birth, nor adult literacy or school enrolment are modeled), an alternative method to estimate the potential HDI that can be reached by a society has been developed. Assuming that the quality of life has a material dimension (minimum energy requirements), data for the final energy footprint of 40 countries for the timeframe 1995–2009 have been used to estimate a regression between the potential HDI levels and the energy use per person.

3. MEDEAS-W model simulation

The potentialities and novel insights that arise from the MEDEAS framework are illustrated by the simulation within MEDEAS-W of 4 cases under a common business-as-usual (BAU) narrative, *i.e.*, assuming that current trends will continue in the next decades.‡‡‡‡ The exploration of alternative storylines (*e.g.*, Green Growth, regionalization, *etc.*[198,199]) would be a much more complex exercise requiring a focus on a broader set of dimensions and uncertainties which is beyond the scope of the present work. Similarly, the implications on regional scale models (EU, country-level) will be explored in future works.

3.1. Definition of scenario cases

BAU is a baseline storyline usually applied in modeling as a counterfactual scenario against which policy scenarios are developed and tested.[8,199,200] Thus, fast radical or structural transformations are excluded by definition in this scenario. For the specification of the BAU narrative through a consistent set of inputs, a varied and rich literature has been examined: scientific papers and technical documentation;[60,63,72,201–203] reports and databases from international/national agencies and organizations such as the International Energy Agency, IRENA, the US Energy Information Administration or the UNEP;[79,92,160,161,204–207] industry prospect assessments[208] and analyst investors,[209] which in some cases were complemented with own estimations (see Appendix A for details).

In this work, four scenario cases of the BAU narrative are simulated: the reference scenario (Ref) and three extreme sensibility cases deactivating two key features operating in the MEDEAS framework and which are subject to scientific uncertainty and discussion: (1) NRE and RES availability restrictions (_noER), and (2) climate change damages (_noCC): Ref_noER, Ref_noCC and Ref_noER_noCC (see Table 3). This scenario case architecture allows us to identify the implications of considering each hypothesis as well as their interaction, which will be discussed in Section 3.2.4.

Fossil fuel resource abundance, understood as the vast geological availability accessible at an affordable price, is a default assumption in most IAMs and energy models.[29,32,64,210]

†††† For more details on the social and environmental impact indicators, see Capellán-Pérez *et al.*,[52] and de Blas Sanz *et al.*[53]

‡‡‡‡ This is different from projecting static current values into the future. For example, the dependence of transportation on oil is currently very high. However, given the current trends of expansion of alternative vehicles, it seems reasonable to assume that this dependence will decrease over the next few decades.

Table 2 Social and environmental impact indicators by dimension available in MEDEAS-W

Dimension	Indicator
Economy	GDP per capita[a]
	Annual growth rate of real GDP per capita (8.1.1 indicator from the SDGs indicators[193])
	Energy intensity measured in terms of both primary and final energy and gross domestic product (GDP) (7.3.1 indicator from the SDGs indicators[193])
	Jobs associated to RES technologies
Energy	Final consumption per capita
	Primary consumption per capita
	Electricity consumption per capita
	Consumption of RES per capita
	Share of RES in total final consumption
	Annual penetration of RES in the total final and primary energy sources consumption
	$EROI^{st}$ of individual RES electric technologies and of the whole system
Land-use	Land requirements for RES production
Minerals	Mineral use per capita
	Cumulated primary mineral extraction *vs.* current reserves
	Cumulated primary mineral extraction *vs.* current resources
Water	Total water and by type consumption per capita
	Share water use *vs.* renewable water resources
Climate change	CO_2, CO_2e and GHG emissions per capita
	CO_2 emission per unit of value added (9.4.1. indicator from the SDGs Indicators[193])
	Atmospheric GHG concentration levels
	Temperature increase over pre-industrial levels
Synthetic	Potential HDI level given energy use

[a] Annual GDP per capita represents the per capita monetary measure of the market value of all final goods and services produced in a year. Hence, GDP represents a "purely economic" approach to measure social welfare. We stress that GDP per capita is not, and was never, designed as a measure of social or economic welfare, despite being the most common indicator of progress for policy-makers and Governments. In fact, above a certain level, reductions in GDP may be welfare enhancing.[194–197]

Table 3 Scenario cases of the BAU narrative simulated in this work: the reference scenario (Ref) and three extreme sensibility cases, deactivating (1) restrictions to the availability of non-renewable and renewable energy sources (no energy resources restrictions: noER), and/or (2) climate change damages (noCC)

Scenario case name	Restrictions to the availability of energy (NRE and RES)?	Climate change damages?
Ref	**YES**	**YES**
Ref_noER	NO	YES
Ref_noCC	YES	NO
Ref_noER_noCC	NO	NO

However, many uncertainties exist in relation to non-renewable energy endowments and their future availability related to technical, geological, economic and political factors. In fact, the IPCC-AR5[8] highlighted that future non-renewable energy availability has historically been under-studied under the assumption of future abundance. This mainstream view is confronted by the fact that biophysical constraints impose certain absolute limits on the use of non-renewable energies, which cannot be extracted at will.[31,32,61,62] While the different estimations for conventional oil and gas tend to converge, respectively, to similar levels, the highest uncertainty is in the future development of unconventional fuels.[30,31] The main issue is to what extent technological improvements will be able to compensate for the fact that pumping, due to the physical properties and geological characteristics of unconventional fuels, becomes substantially more energy consuming and slower.[63,210–212] In this work, the updated forecasts produced by J. Laherrère,[105] a senior geologist which has been analyzing the depletion of oil and gas for decades and whose estimates have been pretty consistent over time[52,62] are applied. For coal, usually seen as a vast abundant resource, recent studies are pointing to potentially large overestimates in coal resource assessments as geologists uncover restrictions on the coal that is extractable.[30,213] For the sake of simplicity, in this work, the highest estimate found in the peer-review literature is considered (high case from Mohr *et al.*,[63]). With relation to uranium, there is only one group of researchers estimating depletion curves of uranium using data regularly published by the Nuclear Energy Agency,[92,95,104] so the most recent estimate from EWG[92] is taken. These depletion curves are converted to maximum extraction curves following the method described in Section 2.2.3.

The techno-ecological potential of RES is also a controversial subject in the literature. The dominant view, which is reflected in most IAMs, considers renewables as a huge, abundant source of energy globally, the technological limits being generally assumed to be unreachable for decades, while the concern focuses on the economic, political or ecological constraints.[35,37,143,214,215] This view is, however, challenged by an increasing body of literature which highlights the fact that the large-scale deployment of RES needed to replace fossil fuels in the current socioeconomic system faces serious challenges in relation to a diversity of factors: their integration in the energy mix due to their intermittency, seasonality and uneven spatial distribution;[110,216,217] their lower energy density – which also exacerbates the global competition for land;[36,38,107,108,110,218,219] their dependence on minerals and materials for the construction of power plants and related infrastructures that pose similar problems than non-renewable energy resources depletion;[34,39,40,129] and finally their associated environmental impacts.[220–225] All together, these factors tend to significantly reduce the techno-sustainable potential of RES.[33–35,37,52,64,110,149,150,217,226,227] In this work, the techno-sustainable potentials of RES for the generation of electricity, heat and biofuels, considering the aforementioned factors estimated in Capellán-Pérez *et al.*,[52] are applied.

Hence, there is a debate in the literature if energy resources could power the increasing demand of Humanity during the 21st Century. The above literature review shows that most models as well as institutional organizations lie in the first group, while the second view is in clear minority. Both visions are in fact related with different paradigms with relation to the assessment of scarcity of natural resources, *i.e.* relative[228,229] *versus* absolute[87,230] scarcity.

With relation to climate change damages, models focusing on cost-effective policies generally omit the modeling of climate damages for the sake of simplicity,[8,181] while those models including them as highly aggregated damages in cost-benefit IAMs have been shown to severely underestimate them.[8,17–21,182,185,231,232] Here, we apply a damage function which has been calibrated assuming that, when the global average surface temperature change reaches +1.75 °C over pre-industrial levels, the climate damages on GDPpc would offset the expected GDPpc growth in that year.[186] The calibration is justified by the fact that increasing scientific evidence is showing that a temperature increase of 1.5/2 °C may be dangerous for human societies,[4,179,180,233] given that the current socio-economic paradigm requires a growing economic system to be functional.[234,235]

Hence, the 3 variants of the BAU reference scenario simulated in this paper explore the implications for the future of taking 2 radically different assumptions with relation to energy availability and climate change:

• Ref_noER is a world of unlimited energy resources to 2100 but subject to climate change damages as GHG cumulate in the atmosphere.

• Ref_noCC is a world of limited energy resources in which climate change does not impact human societies. This case is conceptually similar to other BAU scenarios performed with biophysical energy models such as STER, ECCO or GEMBA[42,43,236] which do not consider constraints such as climate change damages or mineral availability.

• Ref_noER_noCC refers to a world of unlimited energy resources to 2100 and in which climate change does not impact human societies. Generally, these are the most common assumptions followed by the IAMs in the literature.

Table 4 depicts the description of the most relevant inputs and assumptions which characterize the BAU narrative in this work (Ref scenario) (see Appendix A for details). Three alternative scenario cases are implemented, relaxing the respective constraints. The simulation timeframe is set to 2100 as is customary when assessing climate change.

3.2. Results

This section shows the results obtained with MEDEAS-W (v1_3_33) by applying the Reference case of the BAU scenario as well as the three cases relaxing constraints described in Section 3.1. When data are available, the results are compared with the IPCC-AR5 range of baseline scenarios for 2100[8], corresponding to the current state-of-the art of IAMs' BAUs in the literature. Given the global-aggregated scope of the model, all presented results are global-average values.

3.2.1. Total primary energy supply. Fig. 7 shows the Total Primary Energy Supply (TPES) for the 4 scenario cases. Currently, TPES amounts to ∼550 EJ per year globally. TPES increases strongly in Ref_noER_noCC by over 5-fold by 2100 with relation to current levels. In the absence of biophysical constraints, the expected increase in the consumption of goods and services is fulfilled (see Fig. 8B) driving an increase in both primary and final energy requirements (see Fig. 8A). The contribution of RES to the mix increases dramatically in the first decades surpassing 50% by 2060, and thereafter slowing, reaching a penetration of ∼70% by 2100. In the other scenario cases, the TPES also increases, but this growth is only temporary and is ultimately hampered by one or a combination of restrictions which act as limits to growth (see Section 3.2.4). In Ref_noER, the TPES increases strongly until the mid-century, reaching almost 1000 EJ per year, being followed by a sharp reduction thereafter of ∼3% per year and reaching ∼200 EJ per year by 2100. In the scenario cases subject to energy availability constraints, TPES increases less rapidly in the first decades of the 21st Century, thereafter being followed by a less pronounced reduction (1% per year in Ref_noCC and 2% per year in Ref). Still, in the 3 scenario cases accounting for some constraint, the TPES in 2100 is found to be substantially lower than current levels despite an assumed population increase during the analysis period (reaching 9.2 billion people in 2050 and 9.0 in 2100 from the current 7.5[201,202]). RES penetration in these 3 scenario cases range from 60% to 80% by 2100.

3.2.2. Total final energy consumption, GDPpc and system efficiency. Global-average total final energy consumption per capita (TFECpc) increases constantly in the Ref_noER_noCC scenario case during the simulation period, surpassing 220 GJ per year per person, which corresponds to over a 4-fold increase on current levels (Fig. 8A). However, climate change impacts limit further increases of the TFECpc in Ref_noER, which, after attaining a maximum of ∼65 GJ per person per year by ∼2050, falls to <20 GJ per person per year by 2100. For the scenario cases including energy availability constraints, TFECpc is roughly maintained at current levels over a large part of the 21st Century, followed by a decline in the last quarter-century. Still, TFECpc levels are similar to or above the Ref_noER scenario case by 2100 (15–30 GJ per person per year). The change of global-average GDPpc over time follows the change of TFECpc (Fig. 8B), although with a relative decoupling, as shown by the evolution of the ratio between the total final energy consumption (TFEC) and GDP (TFEC intensity, Fig. 8C). The obtained GDPpc level for the Ref_noER_noCC scenario case is in the middle of the range of the BAU scenarios of the literature (Fig. 8B), which span 20 000–50 000 $ per capita by 2100. However, the scenario cases including constraints fall to <5000 $ per capita in the same year, well below the current

Table 4 Description of the most relevant inputs and assumptions of the BAU narrative with energy availability restrictions and climate change damages (Ref scenario) in this work. Dimensions marked with an asterisk (*) indicate that these restrictions are relaxed in the rest of the scenarios (Ref_noER, Ref_noCC and Ref_noER_CC)

Scenario inputs & assumptions	BAU scenario	
Population (2015–2100)	SSP2 (+0.3% per year average over the period)[201,202]	
Expected GDPpc growth (2015–2100)	+2% per year (own estimation, see text)	
Target labor share	52% in 2050, constant thereafter (own estimation based on WIOD[60,203])	
A matrix (2100)	Global A matrix in last year available (2009) (own computation from WIOD[60,203])	
Efficiency improvements (final energy intensity)	Historical efficiency improvement trends by sector/households and final energy[84]	
Inland and households transport		
Oil dependence target per aggregated category in 2100: (continuation of oil dependence although at a decreasing share. Own estimations from [52,160,161]).		
4-Wheel vehicles	34%	
2-Wheel vehicles	0%	
Heavy vehicles	74%	
Bus	54%	
Recycling rates of minerals (19 minerals)	Current recycling rates[237]	
Nuclear capacity	Constant current capacity[208,209]	
***Non-renewable energies depletion curves**		
Oil	Laherrère (2018)[105]	
Natural gas	Laherrère (2018)[105]	
Coal	Mohr *et al.*, (2015) High case[63]	
Uranium	EWG (2013)[92]	
GHG emissions from other gases than CO_2 and CH_4 from fossil fuel combustion	RCP8.5 pathway[238]	
***Climate change impacts**	Damage function calibrated to +1.75 °C as "dangerous climate change level"[186]	
Renewables for electricity generation		
Technology	*Annual capacity growth (2015–2100) (annual historic short-term averaged growth (2012–2015)[79,205,207])[a]*	**Techno-sustainable potential[52]*
Hydroelectric	Annual historic short-term averaged growth (+3.8% per year)	1 TWe
Geothermal	Annual historic short-term averaged growth (+4.2% per year)	0.3 TWth
Bioenergy	Annual historic short-term averaged growth (+7.8% per year)	Shared potential for heat, liquids and electricity (30 EJ per year)
Oceanic (wave, tidal and OTEC)	+10% per year	0.05 TWe
Onshore wind	+10% per year	1 TWe
Offshore wind	+10% per year	0.25 TWe
Solar PV	+10% per year	100 Mha
Solar CSP	+10% per year	
Pumped Hydro Storage (PHS)	+5% per year[b]	0.25 TWe
Renewables for heat generation		
Technology	*Annual capacity growth (2015–2100) (commercial//non-commercial) (annual historic short-term averaged growth (2011–2014)[79,206,239])[a]*	**Techno-sustainable potential[52]*
Solar thermal	+10% per year//+10% per year	Endogenous depending on urban land
Geothermal	+5.2% per year//+7.7% per year	4.4 TWth
Modern solid bioenergy	+5.8% per year//+11.8% per year	Shared potential for heat and electricity (30 EJ per year)
Bioenergy		
Type	*Annual historic short-term averaged growth (2012–2015)[240]* and IEA ETP (2017)[204]	**Techno-sustainable potential[52]*
Conventional bioenergy	—	30 EJ
2nd generation cropland	+3.5% per year	100 Mha
3rd generation cropland (starting 2025)	6% per year	
Residues (starting 2025)	6% per year	25 EJ per year
Marginal lands (starting 2025)	6% per year	386 Mha (~4 EJ per year)[106]

[a] Limited to a maximum of +10% per year, given that very high exponential growth of early technologies cannot be maintained over time as the technology enters the mature phase. [b] Higher than historic trends (1–2% per year[205,207]), given that we assume that, even in a BAU context, to cope with a higher share of variable RES will require the promotion of large scale storage options such as PHS.

global-average of ~7000 $ per capita ($ are USD chained linked volumes (1995)).

TFEC intensity levels decline in all scenario cases until mid-century. However, the high penetration of RES prevents further improvements of TFEC intensity beyond ~2050: the material and energy investments required for the transition to RES imply a re-materialization of the economy that compensates for the efficiency improvements (Fig. 8C). On the other

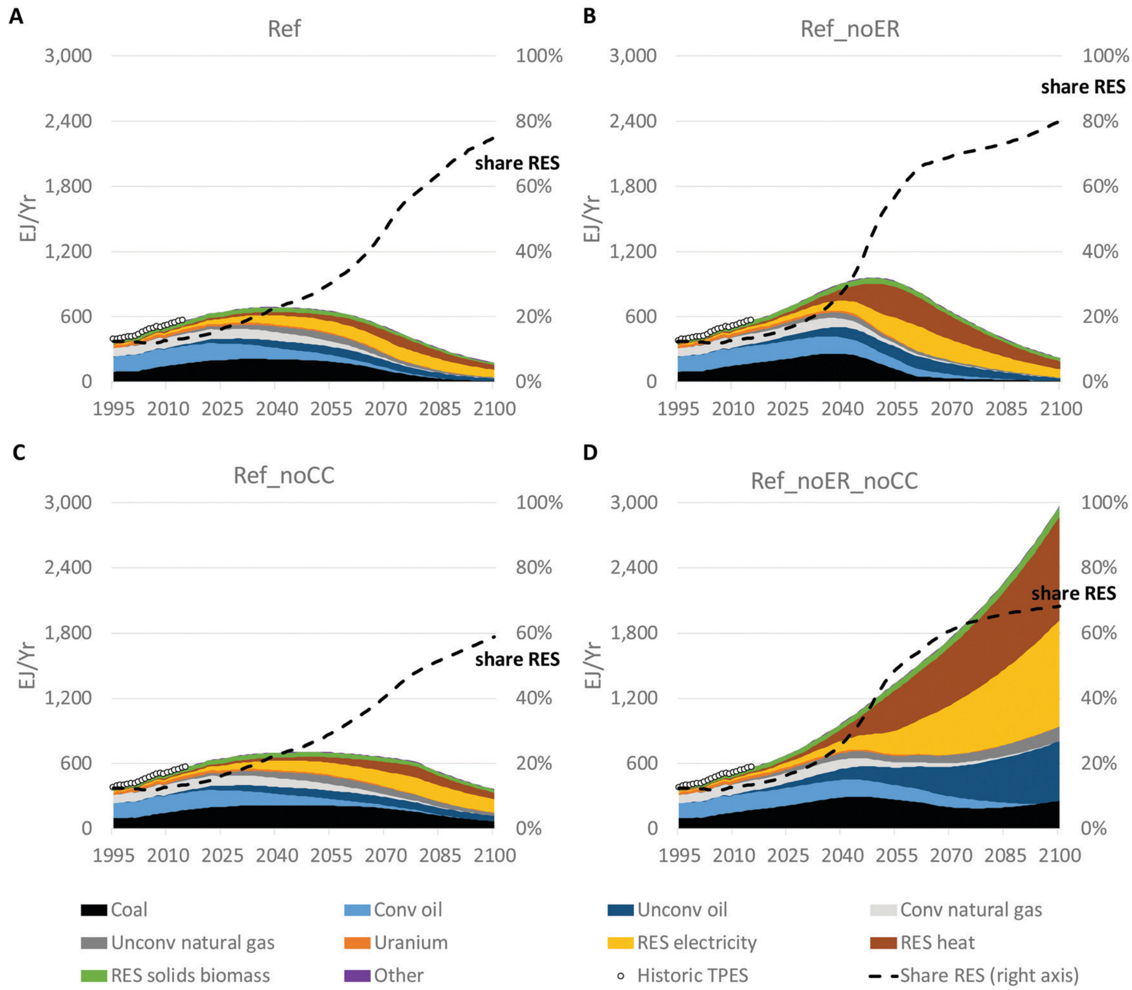

Fig. 7 Total Primary Energy Supply (TPES) mix (EJ per year, left *Y* axis) and share of renewables in the primary energy mix (%, black dashed line, right *Y* axis) 1995–2100 for each scenario case. (A) Ref. (B) Ref_noER. (C) Ref_noCC. (D) Ref_noER_noCC. "Other" includes waste and biogas. Source: own elaboration.

hand, the transition to RES allows for a continuous reduction of the TPES intensity, for all scenario cases, through the timeframe of the analysis. This is, however, not so fast as typically assumed in other models' BAUs (see Fig. 8D).

Despite both the final (TFEC) and primary (TPES) energy intensities depicting a decreasing trend through the simulation period, the system efficiency, as measured by other indicators, does not improve. For example, the primary to final energy ratio (TPES/TFEC, see Fig. 8E) by 2100 is similar to current levels (1.5) for the scenario cases Ref_noER_noCC, Ref_noER and Ref_noCC, and only in Ref does the ratio improves to 1.25. Likewise, the EROI of the whole energy system also falls from current 12 : 1 levels to between 6 and 8 : 1 by 2100 (Fig. 8F). The latter range translates into an over-demand of 5–12% to supply the same level of net energy to society. An inverse relationship exists between the installation rate of new RES capacities and the EROI of the system, due to the up-front energy investments associated to the new RES capacities, which is more accentuated when the potential of those RES technologies with higher EROI, such as wind or hydro, is in full operation. Note that during a fast transition to RES, the EROI of the full system can be temporarily well below the weighted average of the static EROI of the technologies and their supporting systems. This happens in the Ref_noER case, where the EROI reaches a minimum by 2055 (see Fig. 8F) coinciding with the fastest RES growth in the system (see Fig. 7B), and recovering thereafter.[46]

It is noteworthy that in Fig. 7, 8A and B, the results for the Ref case differ substantially from the other three cases (Ref_noCC, Ref_noER, and Ref), while the results for all four cases are roughly similar in Fig. 8C–F. This is due to the fact that TPES, TFECpc and GDPpc are extensive variables which depend on the size of the human system, while the rest of variables (share of RES, intensities and EROI) are intensive variables characterizing the system which do not depend on its size. As a result, given that in the Ref_noER_noCC case the human sphere grows relentless within the biosphere, the extensive variables increase very fast. However, this variation is much smaller for the intensive variables since we are

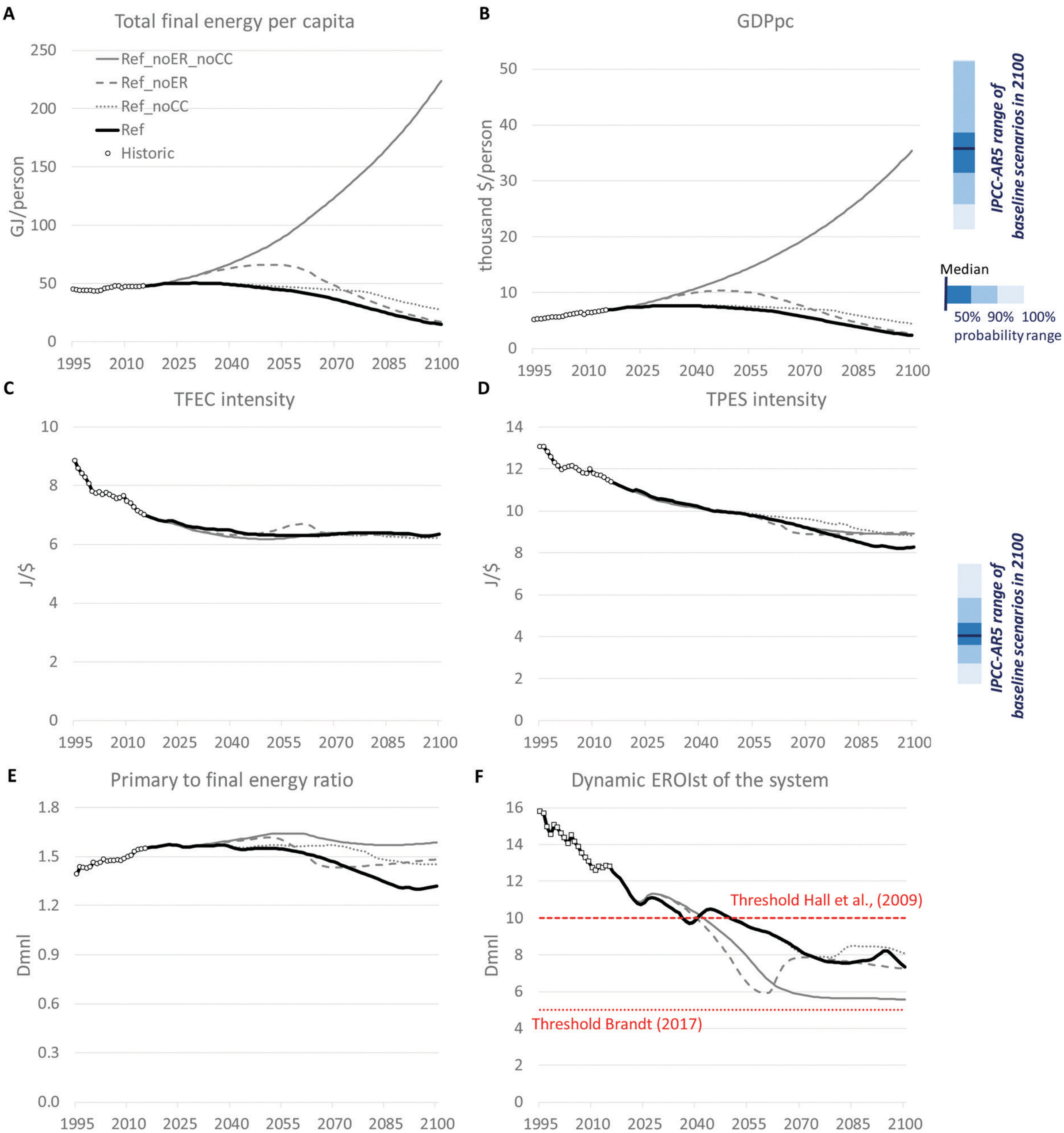

Fig. 8 Final energy consumption per capita, gross domestic product per capita and system efficiency 1995–2100 for the four scenario cases. (A) Total final energy per capita (TFECpc, GJ per person per year). (B) Gross Domestic Product per capita (GDPpc, thousand $ per person, in USD chained linked volumes (1995)). (C) Total final energy consumption (TFEC) intensity (defined as TFEC/GDP, in J per $). (D) Total primary energy supply (TPES) intensity (defined as TPES/GDP, in J per $). (E) Primary to final energy ratio (defined as TPES/TFEC, dimensionless). (F) Dynamic energy return on energy invested ($EROI^{st}$) of the system (dimensionless ratio). Representation of system EROI thresholds to sustain high levels of development in current industrial complex societies from Brandt[154] (∼5 : 1) and Hall *et al.*,[135] (∼10 : 1). Dollars correspond to 1995 US$. Comparison with the IPCC-AR5 range of baseline scenarios for 2100[8] in panels (B and D) median and 50%, 90% and 100% confidence intervals (values have been converted to MEDEAS equivalent units). Source: own elaboration.

assuming a same common scenario BAU as a benchmark for the 4 simulated cases.

3.2.3. Environmental impacts. The consumption of energy translates into environmental impacts. Total land-use requirements by biofuels, solar on land and hydro range ∼450–1150 Mha for the 4 scenario cases (Fig. 9A), which is above the current surface dedicated to urban uses (∼300 Mha, *i.e.*, equivalent to roughly 6× times the surface of a country such as Spain). Ref_noER_noCC represents the maximum of that range, which is in the order of magnitude of the current global arable land.[241] In terms of climate change, GHG emissions roughly double by 2100 in Ref_noER_noCC with relation to current levels, resulting in temperature increases in line with BAU scenarios of the literature (Fig. 9C and D; corresponding to

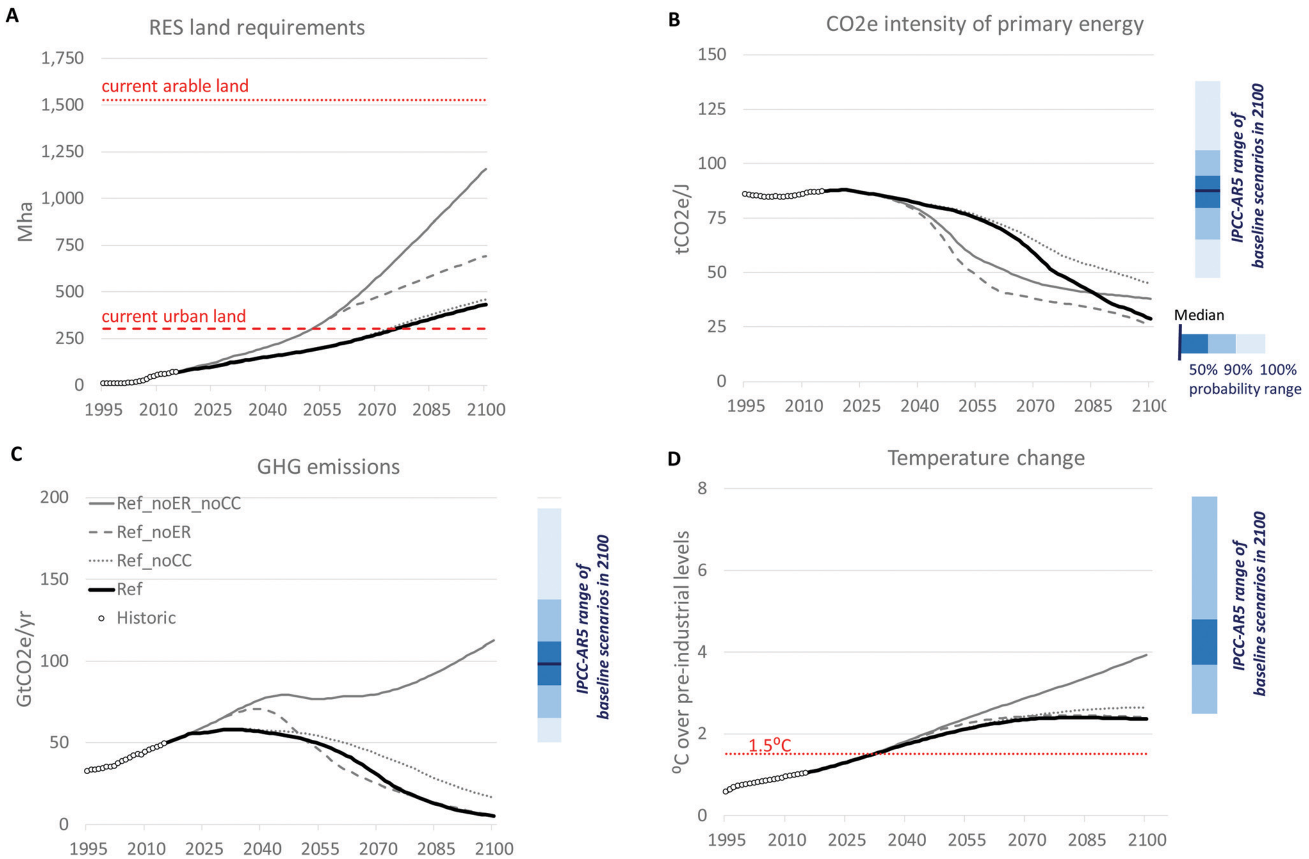

Fig. 9 Environmental impacts 1995–2100. (A) Total RES land requirements (million ha, Mha), as comparison, the current urban and arable land is represented;[241] (B) CO2eq intensity of primary energy (tCO2e per J); (C) GHG emissions (GtCO2e per year); (D) temperature change over pre-industrial levels (°C). Comparison with the IPCC-AR5 range of baseline scenarios for 2100[8] in panels B, C and D: median and 50%, 90% and 100% confidence intervals (values have been converted to MEDEAS equivalent units). Source: own elaboration.

a total radiative forcing of 6.7 W m^{-2}, falling between the RCP6.0 and 8.5 where the IPCC-AR5 baseline scenarios lie[8]). On the other hand, GHG emissions in the 3 scenario cases with constraints peak in 2022–2038 (Fig. 9C), depicting a sharp reduction in 2100 with relation to current levels (65–90%), which translates into lower projections of temperature increase than conventional BAU scenarios (Fig. 9D). Due to limited energy availability, climate change impacts, or the combination of both, human activities cannot follow past trends, and a reduction in the production of goods and services translates into lower temperature increases, which however soon surpass the 1.5 and 2 °C thresholds before mid-century. The CO2e intensity of primary energy declines for all simulations, falling from the current ~90 to 25–45 tCO2e per J by 2100, which is below the range of IPCC-AR5 baseline scenarios (Fig. 9B).

The energy transition will require additional mineral requirements, besides the ones demanded by the rest of the economy. Table 5 shows that, despite the different levels of deployment of RES in the 4 simulations studied, some minerals are expected to undergo supply constraints in the future: copper, indium, manganese, molybdenum, nickel, silver, tin or tellurim.

3.2.4. Interaction of limits to growth. Energy availability constraints and climate change damages operate as potential limits to growth in the MEDEAS framework.§§§§ In the Ref_noER_noCC scenario case, these limits are not activated so the results obtained match the initial expectations: the expected economic growth of +2% per year per person is achieved during the whole simulation period (Fig. 10A). Energy scarcity starts to play a relevant role in both Ref_noCC and Ref at the beginning of the simulation period, significantly affecting the expected economic growth (Fig. 10B). This is due mainly to liquids scarcity, caused by the inability of efficiency improvements and alternatives to liquids, both in terms of direct replacement (*e.g.*, liquid biofuels) and inter-final energy substitutions (*e.g.*, to alternative final energies such as electricity), to compensate for the geological depletion of oil as estimated by Laherrère.[105] Still, the internal mechanisms of the system to balance energy scarcities allow for

§§§§ The variation of EROI at system level, as currently modeled, does not act as a separate limit to growth, given that in the absence of the other two constraints (as in the Ref_noER_noCC scenario case), the expected GDPpc is achieved. However, this is achieved at the cost of more energy expenditure and environmental impacts.

Table 5 Risk assessment of mineral scarcities by 2100 for each scenario case. Comparison of the cumulative extraction by 2100 with the level of reserves and resources. "Red" indicates that cumulated primary extraction > resources and "orange" indicates that reserves < cumulated primary extraction < resources

	Ref	Ref_noER	Ref_noCC	Ref_noER_noCC
Aluminium	Green	Green	Green	Green
Cadmium	Orange	Orange	Orange	Orange
Chromium	Green	Green	Green	Green
Copper	Orange	Orange	Orange	Red
Galium	Orange	Orange	Orange	Orange
Indium	Red	Red	Red	Red
Lithium	Orange	Orange	Orange	Red
Magnesium	Green	Green	Green	Green
Mangenese	Red	Red	Red	Red
Molybdenum	Red	Red	Red	Red
Nickel	Orange	Red	Red	Red
Lead	Orange	Orange	Orange	Orange
Silver	Red	Red	Red	Red
Tin	Orange	Orange	Orange	Red
Tellurium	Red	Red	Red	Red
Vanadium	Green	Green	Green	Orange
Zinc	Orange	Orange	Orange	Orange

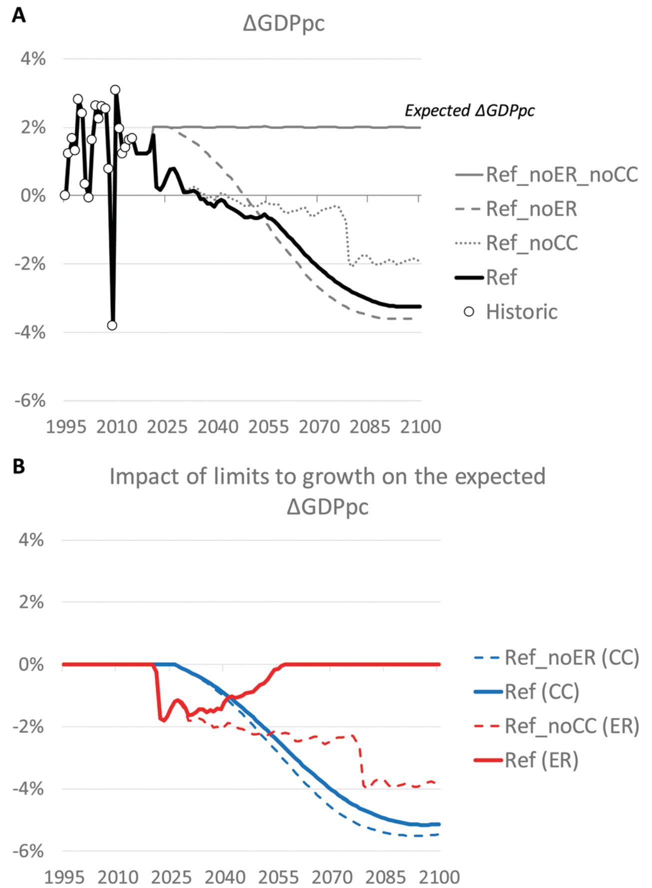

Fig. 10 Annual GDPpc variation and impact of limits to growth for each scenario case (1995–2100). (A) Achieved annual GDPpc growth rate (ΔGDPpc) for each scenario case. (B) Impact of limits to growth on the expected annual GDPpc growth (ΔGDPpc) due to energy scarcity (red lines, ER) and climate change damages (blue lines, CC).

relatively low GDPpc reductions (<0.5% per year) during the first half of the 21st Century in both scenario cases. In Ref_noCC, the GDPpc loss caused by energy scarcity is roughly stable during most of the simulation period close to 2% per year, but surges to ∼4% from 2080 onwards (Fig. 10B). This is mainly due to the fact that from that point the scarcity of gases in this scenario case starts to be a more restrictive constraint for the economy than liquids. Large hydroelectricity and wind onshore are the only RES which are close to deplete their techno-sustainable potential in Ref_noCC, which happens around the mid-21st Century.

When activating climate change damages, those increase progressively as GHGs build up in the atmosphere, ultimately destabilizing global climate, as seen in Section 3.2. Consequently, climate damages cancel out the expected GDPpc growth by the mid-century, causing a global recession afterwards in both scenario cases, reaching −3 and −3.5% GDPpc per year by 2100 for the Ref and Ref_noRE, respectively.

How do both limits to growth interact in the Ref scenario case? Energy scarcity is the most relevant constraint in this case from the 2020s to the early 2040s. During these years, as mentioned above, liquids scarcity hampers the expected GDPpc; renewables and efficiency improvements do not to fill the gap. Still, as seen in previous sections, the global economy continues to function and burn fossil fuels. The warming in the pipeline from GHG emitted in previous decades and the continued accumulation of GHGs in the atmosphere driving temperature increase, even in a likely context of crisis, makes that in the 2040s, climate change damages outpace energy scarcity as the main limit to growth, which ultimately stops having an effect in the 2050s. Climate damages exacerbate the tensions that harm the economy to such a level that, by then, energy availability is no longer an issue. In the late 2050s, climate change damages themselves hamper the expected GDPpc growth, and by 2100, climate damages cause GDPpc losses of ∼5% per year with relation to the expected GDPpc growth, *i.e.*, GDPpc is decreasing at −3% GDPpc per year. Interestingly, although in the Ref scenario the GDPpc is not able to grow during most of the century, the rate of GDPpc reduction in the second half of the 21st Century is smaller than for the Ref_noER scenario case. This is due to the fact that there is a trade-off between fossil energy availability and climate change: if more fossil energy is available and burned by the economy, on the one hand it makes the economy work, but on the other it increases the level of GHGs in the atmosphere, worsening climate change, whose impacts affect the system with a delay due to the inertia of the climate.

4. Discussion and novel insights from the MEDEAS modeling framework

The represented results are obviously subject to a certain degree of uncertainty. The assurance of the outputs can be assessed to be roughly inversely proportional to the distance from the present time. $n = 1000$ Monte Carlo simulations were run in order to perform an uncertainty analysis of the obtained results with relation to the uncertainty of 72 inputs. In general, a good level of stability and robustness is obtained for the 4 scenario cases, despite the wide input and assumptions uncertainty ranges considered (see ESI†).

4.1. Comparison with BAU scenarios from the literature and implications

As shown in Section 3.2, in the absence of energy availability constraints and climate change damages, the results obtained with MEDEAS-W are broadly similar to the BAUs of other IAMs in the literature.[8] However, when activating any of them, the results are completely modified. Unlike the current state-of-the-art, BAU ceases to be a scenario with low renewable penetration in the energy mix, GDPpc 4 to 8 times greater than today, with a 3.5–4.5 °C temperature increase by 2100. The MEDEAS-W results show, instead, a large penetration of renewables in the energy mix (60–80%) that drives large requirements of minerals, energy investments and land; additionally, climate change and energy restrictions damage the human economy by not allowing us to emit GHGs at the current rates, which translates into temperature increase levels <2.5 °C by the end of the 21st Century.

GDPpc and TFECpc decrease from mid-century onwards, reaching levels below current requirements to cover basic needs in the current dominant socio-economic system.[188,190] In the current context of globalization and growth-oriented economies,[234,235] such a long period of crisis or recession would destabilize human societies, most likely driving them towards different socio-political regimes and thus altering the global geopolitical order. A BAU future where most countries maintain the growth-imperative in a context of likely biophysical scarcities (energy, minerals, land, *etc.*) would most likely boost conflict over the remaining available resources, deriving in a 'regionalization scenario' as identified by van Vuuren *et al.*:[199]

"Scenarios in this family assume that regions will focus more on their more self-reliance [sic], national sovereignty and regional identity, leading to diversity but also to tensions among regions and/or cultures. Countries are concerned with security and protection, emphasizing primarily regional markets and paying little attention to common goods. [...] Among the more extreme scenarios are the conflict scenarios identified by the GSG [Global Scenario Group] (barbarization). A key issue in these scenarios is how much self-reliance is possible without becoming harmfully ineffective with respect to supranational issues of resource depletion and environmental degradation. The category, like others, includes different variants – but these are rarely optimistic with respect to global poverty reduction and environmental protection."[199]

Hence, a widespread systemic global socioeconomic and environmental crisis is foreseen in the next few decades in the absence of fast and drastic global sustainability policies. This is in line with other assessments (*e.g.*, ref. 4, 179 and 242–244). However, the novelty is the consistency of the outputs of the IAM with these assessments. It should also be acknowledged that the pressures on the system would likely be too strong for it to remain the same. Hence, at some point after the curves start to fall, the projections and the model lose their prediction capacity.

Still, two main differences with the BAUs from the literature are relevant: a higher TPES (which corresponds with higher TPES intensity levels) (Fig. 7A and 8D) and a lower CO2e intensity of primary energy (Fig. 9B). Despite a decline in TPES intensity in the 4 scenario cases over the simulated period, the reduction is found to be smaller than for other BAUs (22–27% *vs.* 65% for the median of the IPCC-AR5 baseline scenarios[8]). This can be explained by three features explicitly considered in the MEDEAS framework: the energy investments related to the deployment of electric renewables,[44,46] biophysical and thermodynamic limits in the substitution of inputs in production in the medium and long-term,[83,84] and the strong link between economic activity and the use of natural resources, given the difficulties to dematerialize economic production when accounting for sectors' complementarity.[72,245,246] A lower CO2e intensity of primary energy sources levels is obtained due to a higher penetration of RES in MEDEAS BAU scenario cases. This has more to do with scenario specification than modeling assumptions, given that the continuation of current high growth RES is assumed in the next few decades, unlike in other IAMs' BAUs (*e.g.*, ref. 8 and 247).

The obtained results for the Ref_noCC case for the energy outputs are broadly similar to the baselines from biophysical energy models such as STER, CORECCO or GEMBA,[42,43,236] which project a decline in energy availability by the mid-21st Century. These models do not have a distinct economy module, and have a very simplified and stylized way to represent energy demand (typically through aggregated, sometimes biophysical, production functions), while the strength is on the representation of supply, and more specifically on the potential technical and biophysical constraints of supply to follow expected demand. Mineral constraints and climate change impacts are also not represented. The results from the Ref scenario could be conceptually compared with the baseline scenario of World3 ("standard run"),[14,248] given that this model accounts for limited (stock) non-renewable energy availability and impacts through persistent pollution, which delivered an "overshoot and collapse" scenario in the first half of the 21st Century. It is noteworthy that this scenario has performed very well when comparing with 40 years of historical data.[249,250]

4.2. Novel insights from the MEDEAS modeling framework

As shown in previous sections, the consideration of alternative plausible assumptions and methods, combined with the MEDEAS framework's feedback-rich structure, display dynamics that are absent from the classical IAMs.

The transition to renewable energy sources will require large amounts of interrelated energetic, material and economic investments in order to build, operate and interconnect the new energy infrastructures. This finding is consistent with previous results from biophysical energy models such as STER, ECCO or GEMBA.[42,43,236] However, most policy-relevant energy models and IAMs focus solely on monetary investments (*e.g.*, IEA, IPCC, national governments, *etc.*). The modeling of the material and energy investments for the energy transition in MEDEAS allows us to dynamically assess potential mineral scarcities affecting most "green" technologies (with findings in the line of other works in the literature[39,40,46,129]) and to compute the net energy available to society. This approach reveals that there is a trade-off between urgent climate mitigation and the viability of the system, *i.e.*, faster deployment rates of alternative energy systems tend to reduce the EROI of the system, highlighting the need to complement classical monetary costs (*e.g.*, ref. 8 and 251–256) with biophysical quality indicators to analyze energy transitions.[43,257,258] Capellán-Pérez *et al.*,[46] showed that a rapid transition to RES would imply a re-materialization of the economy with the potential to counteract the historic trends of efficiency improvement.

The developed method also allows us to detect potential harmful situations of increasing gross energy output, while decreasing the net energy delivered to society, *i.e.*, the so-called "energy trap".[45,138,259] In extreme cases, a too low EROI, even if the gross energy consumption is increasing, may even trigger a collapse of the full system, although this behavior is not captured in the current framework. In this sense, the EROI levels obtained by 2100 are between the thresholds identified in the literature in order to maintain a complex industrial society (5–10 : 1[135,154]).

Mainstream macroeconomic models – also most economic modules in IAMs – are typically based on computable general equilibrium forcing markets clearing, disregard of the sectoral structure of the economy (including the general assumption that energy can be readily substituted by manufactured capital), and optimization.[28] However, the general assumption of perfect substitutability between factors has been widely criticized from an ecological economics perspective, which considers that complementarity better fits with reality.[23,71,260–262] In fact, aggregated production functions fail to capture the relevance of economic structure in energy-environment interactions.[22,263,264] Scholars have also made critical remarks concerning optimization as an unrealistic approach for modeling complex, dynamic systems where feedbacks and time matter.[28,64,265] In MEDEAS, productive capacity is determined by demand and energy availability. Therefore, neither equilibrium nor optimization are imposed. Moreover, a more realistic approach to energy substitution is enabled by a rich modeling of the technological evolution rates and potentials of energy sources. By using an input–output framework, complementarity between productive factors is assumed, which allows assessing the direct and indirect effects in sectoral production, given an economic structure and the evolution of demand.[73,266] In addition, IOA allows environmentally-extended hybrid approaches,[73,267] which facilitates a much more accurate energy demand estimation, since it is conducted based on all sectors' direct and indirect requirements by a vector of as many final energy sources as the modeler desires – in our case 5 types (see Section 2.2.3). Hence, the spillovers between sectors in IOA change the sectoral composition of energy demand. Because the energy requirements of each sector are different, both qualitatively – distinct energy sources – and quantitatively, economic structure can be of the utmost importance.

There has historically been a large discrepancy between natural scientists' understanding of climatic damage and their representation in climate-focused IAMs. Despite the disruptive potential of future climate change, which threatens human societies as we know them nowadays through severely damaging our natural life-support systems, most IAMs either omit or underestimate climate damages. The most influential cost-benefit IAMs including climate damages, such as DICE, PAGE or FUND, calibrate their damage functions in their standard configuration to monetized estimates of damages which suggest that a century of climate change is about as bad for welfare as a year of standard economic growth (1-4% of Gross Domestic Product (GDP) loss).[17,268] These discrepancies inevitably produce confusion in policy-makers and the citizens, as they receive contradictory messages from the scientific community in relation to the potential damages caused by climate change. Given the existing uncertainties and limitations to accurately represent the human–nature systems over the long-term, as well as the need for urgent action, we judge that the only honest and achievable objective of modeling is to strategically provide advice about the nature of the policy decisions to be made in the next few decades. In this context, MEDEAS proposes a novel, simple and transparent methodology to consistently integrate climate damages into the modeling framework with climate assessments by natural scientists.[186] When surpassing 2 °C of global mean temperature increase, a collapse of the system is more likely than reaching 4 or 5 °C without affecting the socioeconomic dimension. However, it should also be borne in mind that reducing all climate impacts to a monetary value presents significant limitations, given that many impacts also affect non-market dimensions.[8,17]

Future work will be focused on the implications derived from the MEDEAS modeling approach, applying regional models both for BAU and policy-intervention scenarios.

As with any other model, MEDEAS models are not intended to precisely predict the future, but rather to understand system behavior and provide policy-guidance to the best options for the energy transition towards a sustainable economy. They are tools to explore strategies, informing qualitative insights through quantitative modeling. Likewise, the MEDEAS framework also presents a number of limitations and uncertainties such as one-way model integration, low quality data (*e.g.*, IOT sectoral granularity and length of time series, IOT associated socioeconomic and environmental accounts, data on minerals' availability and consumption, *etc.*), low development of some modules (*e.g.*, land-use, water), *etc.* Note that the fix of some of the most important limitations would tend to worsen the obtained results, such as integrating the feed-back of mineral scarcity, the computation of the $EROI^{ext}$ of the system instead of $EROI^{st}$, capturing the metabolic implications of the drop of the EROI of the system to very low levels, *etc.* Further work is going directed¶¶¶¶ towards more dynamization in the Economy module, the creation of new modules to enable the endogenization of more dimensions (*e.g.*, Population), deeper integration between modules (*e.g.*, coherence between energy and monetary investments, endogenous change of the matrix **A** driven by energy mix and technological change, integration of land-use and water, *etc.*), expanding the representation of potential limits to growth (mineral availability, investments for the energy transition, labor supply, *etc.*), refining the modeling of climate change damages or the modeling of behavioral policies.

5. Conclusions

Environmental Integrated Assessment Models (IAMs) constitute a powerful modeling tool for integrating multiple disciplines and dimensions to shed light on potential sustainability pathways in the era of global environmental change. However, the consistent integration of all the physical and social processes is challenged by a combination of scientific knowledge gaps and uncertainties, as well as by the inherent unpredictability of future paths to be taken by societies around the planet.

This paper describes the open-source MEDEAS integrated assessment modeling framework, which has been developed with the aim of informing decision-making to achieve the transition to sustainable energy systems with a focus on biophysical, economic, social and technological restrictions and applying alternative modeling assumptions and methods to a core set of common assumptions in IAMs whose validity is being disputed in the scientific discussion: lack of feedback, deficient representation of economic structure, dominance of equilibrium-optimization approaches, the widespread use of prices as indicators of scarcity, energy abundance presumption and neglect of the material and energy investments related to the transition to renewables.

The models are developed in system dynamics, which facilitates the integration of knowledge from different perspectives and disciplines, as well as feedbacks from the different subsystems. MEDEAS models are designed to run until 2060–2100, and are conceptually structured into nine modules: economy, energy demand, energy availability, energy infrastructures and energy return on energy invested (EROI), minerals, land-use, water, climate/emissions, and social and environmental impact indicators. The modules of Economy and Energy are the most detailed. The models include six main features which all together represent a step forward in the state-of-the-art of the field:

- Representation of biophysical constraints to energy availability
- Modeling of the material and energy investments for the energy transition, allowing to dynamically assess potential mineral scarcities and the net energy available to society
- Consistent representation of climate change damages with climate assessments by natural scientists
- Integrated representation of economic processes and biophysical limits to growth, including the integration of detailed sectoral economic structure (input-output analysis) within a system dynamics approach
- Energy shifts driven by physical scarcity
- Rich set of socioeconomic and environmental impact indicators

Hence, the MEDEAS framework incorporates two limits to growth that are rarely considered (even separately) in the literature: energy availability and climate change damages. This is a first step, given that human societies operate within many more biophysical constraints.[1,169]

The simulation of 4 business-as-usual (BAU) scenario cases, switching on/off these two limits to growth in the MEDEAS-World model illustrates the potentiality of the framework. The consideration of alternative plausible assumptions and methods, combined with the framework's feedback-rich structure, display dynamics absent from the classical models. In the absence of energy availability constraints and climate change damages, the results obtained throughout the 21st Century are broadly similar to those obtained by other IAMs' BAUs in the literature.[8] However, when activating any of these constraints, the results get completely modified. Unlike the current state-of-the-art, BAU ceases to be a scenario with low renewable penetration in the energy mix, Gross Domestic Product per capita (GDPpc) 4 to 8 times greater than today's and a 3.5–4.5 °C temperature increase by 2100. The MEDEAS-W results show in the same timeframe, instead, a BAU with a large penetration of renewables in the energy mix (60–80%) driving large requirements of minerals, energy investments and land, a persistent recession over the next decades with global-average GDPpc levels similar or below current levels caused by a combination of energy scarcity and climate damages, which prevent us from emitting GHGs at increasing rates. This contributes to keeping temperature increase levels <2.5 °C by 2100 (omitting the possibility of the occurrence of a fast tipping point in the climate system which would worsen the obtained results). Hence, a widespread systemic global socioeconomic and environmental crisis is foreseen in the next few decades in the absence of fast and drastic global sustainability policies. From the 6 'scenario families' identified by van Vuuren *et al.*,[199] in global environmental assessments, our results suggest that current trends increasingly correspond to the 'regional competition' storyline, where a focus on national sovereignty would give priority to security concerns and trade barriers, which may derive in conflict and even collapse scenarios. Despite depicting a much more worrying future than conventional BAUs, we do

¶¶¶¶ These limitations are being addressed in the ongoing H2020 project 'LOCOMOTION' (H2020-LC-CLA-2018-2, Project Number 821105, https://www.locomotion-h2020.eu), approved by the European Commission with the objective of improving the MEDEAS framework.

however believe it is a more realistic counterfactual scenario that will enable the design of improved alternative sustainable pathways in future work.

Acronyms and glossary

BAU	Business-as-usual. Scenario projecting future changes as the continuation of current trends
C-ROADS	Climate rapid overview and decision support. https://www.climateinteractive.org/tools/c-roads/
CSP	Concentrated solar power
Dmnl	Dimensionless
EROI	Energy return on energy investment. Ratio between the energy delivered from a process divided by the energy required to get it over its lifetime
ESOI	Energy stored on energy invested. Ratio between the energy stored in a storage device divided by the energy required to get it over its lifetime
EU	European Union. EU-28
EV	Electric vehicle
GCAM	Global change assessment model. http://www.globalchange.umd.edu/gcam/
GDP	Gross domestic product. Monetary value of final goods and services – that are bought by the final users – produced in a region in a given period of time
GFCF	Gross fixed capital formation. Investments made by each component of the final demand in durable products produced by each sector
GHG	Greenhouse gas. Gas that absorbs and emits radiant energy within the thermal infrared range
HH	Households
IAM	Integrated assessment model
IEA	International energy agency
IMAGE	Integrated model to assess the global environment. https://models.pbl.nl/image/
IOA	Input–output analysis. Quantitative economic model that represents the interdependencies between different sectors of a national economy or different regional economies
IOT	Input–output tables
IPCC	Intergovernmental panel on climate change. Intergovernmental body of the United Nations that is dedicated to providing the world with an objective, scientific view of climate change, its natural, political, and economic impacts and risks, and possible response options
LCA	Life-cycle analysis. Technique to assess the required resource inputs (*e.g.* energy, materials, water, *etc.*) or related environmental impacts associated (*e.g.*, GHG emissions) with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling
MEDEAS	Modeling energy system development under environmental and socioeconomic constraints. Name of the H2020 project (https://www.medeas.eu/) and by extension of the models developed in that framework
NRE	Non-renewable energy
pc	per capita
PHS	Pumped hydro storage
PV	Photovoltaic
RCP	Radiative concentration pathway. Set of scenarios developed as a standard basis for near and long-term climate modeling experiments (tntcat.iiasa.ac.at:8787/RcpDb/)
Ref	Scenario case used in this paper. With restrictions to energy availability; with climate change damages
Ref_noCC	Scenario case used in this paper. With restrictions to energy availability; no climate change damages
Ref_noER	Scenario case used in this paper. No restrictions to energy availability; with climate change damages
Ref_noER_noCC	Scenario case used in this paper. No restrictions to energy availability; no climate change damages
RES	Renewable energy source
SDG	Sustainable development goal. Collection 17 global goals set in 2015 by the United Nations General Assembly and intended to be achieved by the year 2030
SSP	Shared socioeconomic pathway. Set of scenarios developed as a standard basis for projected socioeconomic global changes up to 2100 (https://tntcat.iiasa.ac.at/SspDb/)
TFEC	Total final energy consumption. Final energy use from the side of demand
TFES	Total final energy supply. Final energy use from the side of supply
TPES	Total primary energy supply. Total final + generation + transport, distribution and transmission losses
WIOD	World input–output database. http://www.wiod.org/

Conflicts of interest

There are no conflicts to declare.

Appendix A: specification of the simulated scenarios

For the quantification of the BAU narrative through a consistent set of inputs, a varied and rich literature has been examined, which in some cases had to be complemented with our own estimations.

For population, the "middle of the road" of the Shared Socioeconomic Pathways (SSP2) was considered, given that this scenario is "intended to represent a future in which development trends are not extreme in either of the dimensions but rather follow middle-of-the-road pathways relative to the span of plausible outcomes for each element".[198] Combining medium fertility with medium mortality, migration and education scenarios for all countries, the SSP2 assumes a world of increasing population, but at a rate that was slowing down, reaching 9.2 billion people in 2050 and 9.0 in 2100 from the current 7.5.[201,202]

The expected gross domestic product per capita (GDPpc) is a key variable of the model, given the connection between economic activities and resource consumption. We select an intermediate value between historic global trends of +1.42% per year (1979–2014) – a period characterized by lower growth trends than those in the post-war "The Glorious Thirty" (1945 to 1975)[72] – and the +2.5% average growth stated by the SSP2, *i.e.*, +2% per year. This means that GDPpc would be expected to reach over 30 000 US 1995 $ by 2100 from a current level of ~7000 $.

In terms of income distribution, the historical decline of labor share, *i.e.*, the part of national income allocated to wages, is extrapolated into the future, but at a reduced pace due to the increasing importance of emergent countries in the global GDP. As these countries, in their respective modernization processes, are improving their labor shares, it is to be expected that they partially compensate for the global decline trend in labor share in the future. Although China is following the opposite trend, this is due to its relatively higher current labor share. Hence, a value of 52% for the world average is assumed for 2050 from the current 56%, which is then kept constant until the end of the century. It is worth saying that scenarios with a capital share higher than the labor share are found in countries with a low developed welfare state and high rates of inequality indexes,[269,270] while current EU and well developed welfare state countries depict values close to 60%.[78]

Given the complexities of consistently computing the dynamic behavior of the matrix **A**, the current global economic structure is assumed to remain constant over the next few decades in the context of a BAU scenario. This is supported by the relatively minor variations to the technical coefficients in the available historical data.[60,203]

Technological improvements are modeled top-down at sectoral level (except for transportation where it is done bottom-up), extrapolating the historical efficiency improvement trends by sector/households and final energies into the future.[52,84]

In inland and households transport, the continuation of the dependence on oil is assumed, although its share is reduced over time *via* the shift to electric, hybrid and gas vehicles. More optimistic prospects are expected for light vehicles than for heavy ones, based on current data and analyses.[52,160,161] For the case of air and water transport, we consider that, within the BAU storyline, there would not be a substantial replacement of conventional fuels by low carbon alternatives, given the technological challenges involved which remain unresolved.[155]

Nuclear installed capacity and electricity generation are constant for over two decades in the absence of major new-build programs apart from China. In this context of increased ageing of existing reactors, increasing costs and general decline in interest in nuclear new-build, the continuation of current trends may drive global nuclear capacity downwards over the next few decades.[208] This trend may be compensated for by eventual lifetime extension programs.[209] For this reason, in the BAU, we consider that the nuclear capacity in operation globally will be constant. This assumption corresponds well with the projection of the international news agency for investors Bloomberg, which estimates, in its "New Energy Outlook 2018", that by the mid-century nuclear will produce a level of electricity similar to current levels.[209]

The installation of RES technology capacity is growing globally, with large variations depending on the technology and the period of time analyzed. Particular conditions, such as the economic recession from the year 2008, have influenced their development pace. However, the fact that, when a technology starts to deploy, each additional power plant represents a high share in relation to the cumulative installed capacity should also be taken into account. This translates into explosive initial exponential deployment rates, which are softened over time as cumulated capacity increases. Annual historic short-term averaged growth (2012–2015) has generally been taken as the reference for electric,[79,205,207] heat[79,206,239] and bioliquid technologies.[204,240] These rates are limited to a maximum of +10% per year, given that very high exponential growth of early technologies cannot be maintained over time as the technology enters the mature phase. Given the environmental impacts of conventional biofuels,[33,271–274] it is likely that, in the future (BAU), current growth rates of this technology will not be maintained, and for these reasons, their growth is halved with relation to the historic short-term averaged growth.[204]

Acknowledgements

The authors gratefully acknowledge Iñaki Arto for assisting with the interpretation and use of the WIOD database, Robert W. Howarth for sharing his data in relation to methane emissions of fossil fuels, Steve Mohr for sharing his world and country-level dataset including the scenarios of potential future extraction of fossil fuels, and Jean Laherrère for sharing his forecasts for oil and gas global production. The authors also thank the MEDEAS project consortium (https://www.medeas.eu) within which the models were developed, and especially its coordinator Jordi Solé, Christian Kimmich for his collaboration in the elaboration of the world level IOT, Lukas Eggler and Roger Samsó for the revision of the models, as well as the contribution of the project partners to the general model validation process. A preliminary version of this work was presented at the 11th Annual Meeting of the Integrated Assessment Modeling Consortium (IAMC) Conference in Seville (November 2018). This work has been partially developed under the MEDEAS project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement no. 691287. This work has also been partially developed under the LOCOMOTION project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement no. 821105. The authors are thankful as well for the support of MODESLOW (Modeling and Simulation of scenarios towards a LOW-carbon transition: The Spanish case), a Spanish national research project funded under the Spanish National Research, Development and Innovation Program (Ministry of Economy and Competitiveness of Spain, ref. ECO2017-85110-R). Iñigo Capellán-Pérez also acknowledges financial support from a Juan de la Cierva Research Fellowship of the Ministry of Economy and Competitiveness of Spain (no. FJCI-2016–28833).

References

1 W. Steffen, K. Richardson, J. Rockström, S. E. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, S. R. Carpenter, W. de Vries, C. A. de Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L. M. Persson, V. Ramanathan, B. Reyers and S. Sörlin, *Science*, 2015, **347**, 1259855.

2 A. D. Barnosky, E. A. Hadly, J. Bascompte, E. L. Berlow, J. H. Brown, M. Fortelius, W. M. Getz, J. Harte, A. Hastings, P. A. Marquet, N. D. Martínez, A. Mooers, P. Roopnarine, G. Vermeij, J. W. Williams, R. Gillespie, J. Kitzes, C. Marshall, N. Matzke, D. P. Mindell, E. Revilla and A. B. Smith, *Nature*, 2012, **486**, 52–58.

3 T. M. Lenton, H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf and H. J. Schellnhuber, *Proc. Natl. Acad. Sci. U. S. A.*, 2008, **105**, 1786–1793.

4 W. Steffen, J. Rockström, K. Richardson, T. M. Lenton, C. Folke, D. Liverman, C. P. Summerhayes, A. D. Barnosky, S. E. Cornell, M. Crucifix, J. F. Donges, I. Fetzer, S. J. Lade, M. Scheffer, R. Winkelmann and H. J. Schellnhuber, *Proc. Natl. Acad. Sci. U. S. A.*, 2018, **115**, 8252–8259.

5 G. Daily, *Nature's services: societal dependence on natural ecosystems*, Island Press, Washington, DC, Island Press, 1997.

6 S. A. Levin, S. R. Carpenter, H. C. J. Godfray, A. P. Kinzig, M. Loreau, J. B. Losos, B. Walker and D. S. Wilcove, *The Princeton guide to ecology*, Princeton University Press, Princeton, N.J. (USA), 2009.

7 S. H. Schneider and L. Morton, *The Primordial Bond Exploring Connections Between Man and Nature Through the Humanities and Sciences*, Plenum Press, New York, 1981.

8 IPCC, *Climate Change 2014: Mitigation of Climate Change*, Cambridge University Press, 2014.

9 A. Janetos, L. Clarke, W. Collins, K. Ebi, J. Edmonds, I. Foster, H. Jacoby, K. Judd, L. Leung, R. Newell, *et al.*, *Science challenges and future directions: climate change integrated assessment research*, Dept. of Energy, Washington, 2009.

10 M. C. Sarofim and J. M. Reilly, *Wiley Interdiscip. Rev. Clim. Change*, 2011, **2**, 27–44.

11 E. A. Stanton, F. Ackerman and S. Kartha, *Clim. Dev.*, 2009, **1**, 166–184.

12 R. S. J. Tol, Integrated Assessment Modelling, Working Paper FNU-102, 2006.

13 U. Bardi, *The limits to growth revisited*, Springer, New York, 2011.

14 D. H. Meadows, D. L. Meadows, J. Randers and W. W. Behrens III, *The Limits to Growth*, Universe Books, New York, 1972.

15 S. Schneider and J. Lane, *Integr. Assess. J.*, 2005, **5**, 41–75.

16 G. S. Cumming, J. Alcamo, O. Sala, R. Swart, E. M. Bennett and M. Zurek, *Ecosystems*, 2005, **8**, 143–152.

17 D. Diaz and F. Moore, *Nat. Clim. Change*, 2017, **7**, 774–782.

18 S. Dietz and N. Stern, *Econ. J.*, 2015, **125**, 574–620.

19 T. M. Lenton and J.-C. Ciscar, *Clim. Change*, 2013, **117**, 585–597.

20 N. Stern, *J. Econ. Lit.*, 2013, **51**, 838–859.

21 M. L. Weitzman, *J. Publ. Econ. Theory*, 2012, **14**, 221–244.

22 M. De Haan, *Econ. Syst. Res.*, 2001, **13**, 181–196.

23 J. Farley and H. E. Daly, *Ecological Economics: Principles and Applications*, Island Press, Washington, 1st edn, 2003.

24 L. Hardt and D. W. O'Neill, *Ecol. Econ.*, 2017, **134**, 198–211.

25 M. Lavoie, *Post-Keynesian Economics: New Foundations*, Edward Elgar Publishing, 2014.

26 R. B. Norgaard, *J. Environ. Econ. Manag.*, 1990, **19**, 19–25.

27 M. J. Radzicki, *Complex Systems in Finance and Econometrics*, Springer, New York, NY, 2009, pp. 727–737.

28 S. Scrieciu, A. Rezai and R. Mechler, *WENE*, 2013, **2**, 251–268.

29 D. McCollum, N. Bauer, K. Calvin, A. Kitous and K. Riahi, *Clim. Change*, 2014, **123**, 413–426.

30 I. Capellán-Pérez, I. Arto, J. M. Polanco-Martínez, M. González-Eguino and M. B. Neumann, *Energy Environ. Sci.*, 2016, **9**, 2482–2496.

31 J. Wang, L. Feng, X. Tang, Y. Bentley and M. Höök, *Futures*, 2017, **86**, 58–72.

32 M. Höök and X. Tang, *Energy Policy*, 2013, **52**, 797–809.

33 C. de Castro, Ó. Carpintero, F. Frechoso, M. Mediavilla and L. J. de Miguel, *Energy*, 2014, **64**, 506–512.

34 C. de Castro, M. Mediavilla, L. J. Miguel and F. Frechoso, *Renewable Sustainable Energy Rev.*, 2013, **28**, 824–835.

35 C. de Castro, M. Mediavilla, L. J. Miguel and F. Frechoso, *Energy Policy*, 2011, **39**, 6677–6682.

36 L. M. Miller and A. Kleidon, *Proc. Natl. Acad. Sci. U. S. A.*, 2016, 201602253.

37 P. Moriarty and D. Honnery, *Energy Policy*, 2016, **93**, 3–7.

38 A. Scheidel and A. H. Sorman, *Global Environ. Change*, 2012, **22**, 588–595.

39 K. Tokimatsu, H. Wachtmeister, B. McLellan, S. Davidsson, S. Murakami, M. Höök, R. Yasuoka and M. Nishio, *Appl. Energy*, 2017, **207**, 494–509.

40 A. Valero, A. Valero, G. Calvo and A. Ortego, *Renewable Sustainable Energy Rev.*, 2018, **93**, 178–200.

41 T. Trainer, *Humanomics*, 2013, **29**, 88–104.

42 C. D. Rye and T. Jackson, *Energy Policy*, 2018, **122**, 260–272.

43 M. Dale, S. Krumdieck and P. Bodger, *Ecol. Econ.*, 2012, **73**, 158–167.

44 M. Carbajales-Dale, C. J. Barnhart, A. R. Brandt and S. M. Benson, *Nat. Clim. Change*, 2014, **4**, 524–527.
45 M. R. Sers and P. A. Victor, *Ecol. Econ.*, 2018, **151**, 10–21.
46 I. Capellán-Pérez, C. de Castro and L. J. Miguel González, *Energy Strategy Rev.*, 2019, **26**, 100399.
47 C. A. S. Hall, Energy Return on Investment as Master Driver of Evolution, *Energy Return on Investment. A unifying principle for Biology, Economics and Sustainability*, 2017, pp. 59–72.
48 C. A. S. Hall and K. A. Klitgaard, *Energy and the Wealth of Nations: Understanding the Biophysical Economy*, Springer New York, New York, NY, 2012.
49 C. W. King, *Biophys. Econ. Resour. Qual.*, 2016, **1**, 10.
50 NCC, Nature Climate Change, DOI: 10.1038/nclimate2526.
51 S. H. Schneider, *Environ. Model. Assess.*, 1997, **2**, 229–249.
52 I. Capellán-Pérez, I. de Blas, J. Nieto, C. De Castro, L. J. Miguel, M. Mediavilla, Ó. Carpintero, P. Rodrigo, F. Frechoso and S. Cáceres, *D4.1 MEDEAS Model and IOA implementation at global geographical level*, MEDEAS Project, Barcelona, Spain, 2017.
53 I. de Blas Sanz, I. Capellán-Pérez, Ó. Carpintero Redondo, C. De Castro, F. Frechoso, L. F. Lobejón, P. L. Lomas Huertas, M. Mediavilla, L. J. Miguel, J. Nieto and P. Rodrigo, *D4.2 MEDEAS Model and IOA implementation at European geographical level*, MEDEAS Project, Barcelona, Spain, 2018.
54 D. Álvarez Antelo, I. de Blas Sanz, I. Capellán-Pérez, Ó. Carpintero Redondo, C. De Castro, F. Frechoso, L. F. Lobejón, P. L. Lomas Huertas, M. Mediavilla, L. J. Miguel, J. Nieto, G. Parrado and P. Rodrigo González, *D4.3 MEDEAS Model and IOA implementation at country level: the cases of Austria and Bulgaria*, MEDEAS Project, Barcelona, Spain, 2018.
55 R. Samsó, T. Madurell, J. Solé, I. de Blas, I. Perissi, G. Martelloni, U. Bardi and D. Natalini, *D5.2 Models statistics*, MEDEAS project, Barcelona, Spain, 2019.
56 R. Samsó, I. de Blas, J. Solé, I. Perissi and G. Martelloni, *Energy Strategy Rev.*, submitted.
57 J. D. Sterman, *Business dynamics: systems thinking and modeling for a complex world*, Irwin/McGraw-Hill Boston, 2000, vol. 19.
58 Y. Barlas, *Syst. Dynam. Rev.*, 1996, **12**, 183–210.
59 D. Natalini, K. Buchmann, R. Spannenkrebs, S. Nitschke, A. Jones, I. Perissi, S. Falsini, U. Bardi, A. Nikolaev, M. Baumann, L. Egler, H. Angela, C. Ploier, I. Capellán-Pérez, L. J. Miguel González and H. T. J. Henke, *D5.1 Models' cross-comparison and qualitative evaluation*, MEDEAS project, Barcelona, Spain, 2018.
60 E. Dietzenbacher, B. Los, R. Stehrer, M. Timmer and G. de Vries, *Econ. Syst. Res.*, 2013, **25**, 71–98.
61 C. J. Campbell and J. Laherrère, *Sci. Am.*, 1998, **278**, 60–65.
62 C. Kerschner and I. Capellán-Pérez, in *Routdlege Handbook of Ecological Economics: Nature and Society*, ed. C. L. Spash, Abingdon, Routledge, 2017, pp. 425–435.
63 S. H. Mohr, J. Wang, G. Ellem, J. Ward and D. Giurco, *Fuel*, 2015, **141**, 120–135.
64 I. Capellán-Pérez, M. Mediavilla, C. de Castro, Ó. Carpintero and L. J. Miguel, *Energy*, 2014, **77**, 641–666.
65 D. P. van Vuuren, J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S. J. Smith and S. K. Rose, *Clim. Change*, 2011, **109**, 5–31.
66 T. Fiddaman, L. S. Siegel, E. Sawin, A. P. Jones and J. Sterman, *C-ROADS simulator reference guide (v78b)*, 2017.
67 J. Sterman, T. Fiddaman, T. Franck, A. Jones, S. McCauley, P. Rice, E. Sawin and L. Siegel, *Syst. Dynam. Rev.*, 2012, **28**, 295–305.
68 R. Costanza, *Ecol. Econ.*, 1989, **1**, 1–17.
69 R. Costanza, *Ecological Economics: The Science and Management of Sustainability*, Columbia University Press, New York, revised edition, 1991.
70 H. Daly, *J. Polit. Econ.*, 1968, **76**, 392–406.
71 N. Georgescu-Roegen, *The Entropy Law and the Economic Process*, Harvard University Press, Cambridge, Mass, reprint 2014 edition, 1971.
72 J. Nieto, Ó. Carpintero, L. J. Miguel and I. de Blas, *Energy Policy*, 2019, 111090.
73 R. E. Miller and P. D. Blair, *Input-Analysis. Foundations and Extensions*, Cambridge University Press, Cambridge, UK, 2009.
74 J. D. Hamilton, *Historical Oil Shocks*, National Bureau of Economic Research, 2011.
75 D. J. Murphy and C. A. S. Hall, *Ann. N. Y. Acad. Sci.*, 2011, **1219**, 52–72.
76 M. K. Heun, M. Carbajales-Dale and B. R. Haney, *Beyond GDP. National Accounting in the Age of Resource Depletion*, Springer, 2015.
77 D. I. Stern, *Energy Econ.*, 2012, **34**, 2200–2208.
78 A. Genty, I. Arto and F. Neuwahl, WIOD Deliverable 4.6, Documentation, downloadable at http://www.wiod.org/publications/source_docs/Environmental_Sources.pdf.
79 IEA, *IEA World Energy Statistics and Balances*, IEA/OECD, Paris (France), 2019.
80 M. Filippini and L. C. Hunt, *Energy J.*, 2011, 59–80.
81 S. Voigt, E. De Cian, M. Schymura and E. Verdolini, *Energy Econ.*, 2014, **41**, 47–62.
82 I. S. Wing, *Resour. Energy Econ.*, 2008, **30**, 21–49.
83 N. J. Schenk and H. C. Moll, *Ecol. Econ.*, 2007, **63**, 521–535.
84 I. de Blas, L. J. Miguel and I. Capellán-Pérez, *Energy Strategy Rev.*, 2019, **26**, 100419.
85 E. Neumayer, *J. Econ. Surv.*, 2000, **14**, 307–335.
86 D. B. Reynolds, *Ecol. Econ.*, 1999, **31**, 155–166.
87 C. Cleveland and D. Stern, in *The economics of nature and the nature of economics*, ed. C. J. Cleveland, R. Costanza and D. I. Stern, Edward Elgar Publishing, Cheltenham, UK, 2001, pp. 238–261.
88 A. Valero, Ó. Carpintero, A. Valero and G. Calvo, *Ecol. Indic.*, 2014, **46**, 548–559.
89 R. G. Miller and S. R. Sorrell, *Philos. Trans. R. Soc., A*, 2014, **372**, 20130179.
90 K. Aleklett, M. Höök, K. Jakobsson, M. Lardelli, S. Snowden and B. Söderbergh, *Energy Policy*, 2010, **38**, 1398–1414.
91 ASPO, *ASPO Newsletter n. 100*, The Association for the Study of Peak Oil and gas, 2009.

92 EWG, *Fossil and Nuclear Fuels – the Supply Outlook*, Energy Watch Group, 2013.
93 EWG, *Crude Oil – The Supply Outlook*, Energy Watch Group/Ludwig-Boelkow-Foundation, 2008.
94 EWG, *Coal: Resources and Future Production*, 2007.
95 EWG, *Uranium Resources and Nuclear Energy*, Energy Watch Group, 2006.
96 M. Höök, W. Zittel, J. Schindler and K. Aleklett, *Fuel*, 2010, **89**, 3546–3558.
97 J. Laherrère, *Peak Oil y Seguridad Energética*, Buenos Aires, Argentina, 2010.
98 J. Laherrère, *Oil and gas, what future?*, Groningen, Netherlands, 2006.
99 G. Maggio and G. Cacciola, *Fuel*, 2012, **98**, 111–123.
100 S. H. Mohr, *Fossil fuel future production, world and Australia focus*, Australian Frontiers of Science 2012: Science for a green economy, Sydney, 2012.
101 S. H. Mohr and G. M. Evans, *Energy Policy*, 2011, **39**, 5550–5560.
102 S. H. Mohr and G. M. Evans, *Fuel*, 2009, **88**, 2059–2067.
103 T. W. Patzek and G. D. Croft, *Energy*, 2010, **35**, 3109–3122.
104 W. Zittel, Feasible Futures for the Common Good. Energy Transition. Paths in a Period of Increasing Resource Scarcities, Ludwig-Bölkow-Systemtechnik GmbH, Munich (Germany), 2012.
105 J. Laherrère, *Oil & gas production forecasts (1900–2200)*, 2018.
106 C. B. Field, J. E. Campbell and D. B. Lobell, *Trends Ecol. Evol.*, 2008, **23**, 65–72.
107 I. Capellán-Pérez, C. de Castro and I. Arto, *Renewable Sustainable Energy Rev.*, 2017, **77**, 760–782.
108 D.-J. Van de Ven, I. Capellán-Pérez, I. Arto, I. Cazcarro, C. De Castro, P. Patel and M. González-Eguino, Under review.
109 R. Fouquet, *Energy Policy*, 2010, **38**, 6586–6596.
110 V. Smil, *Energy in nature and society: general energetics of complex systems*, MIT Press, Cambridge, Massachusetts, USA, 2008.
111 D. M. Reiner, *Nat. Energy*, 2016, **1**, 15011.
112 V. Scott, S. Gilfillan, N. Markusson, H. Chalmers and R. S. Haszeldine, *Nat. Clim. Change*, 2013, **3**, 105–111.
113 K. Anderson and G. Peters, *Science*, 2016, **354**, 182–183.
114 EASAC, *Negative emission technologies: What role in meeting Paris Agreement targets?*, 2018, vol. EASAC policy report 35.
115 S. Fuss, J. G. Canadell, G. P. Peters, M. Tavoni, R. M. Andrew, P. Ciais, R. B. Jackson, C. D. Jones, F. Kraxner, N. Nakicenovic, C. Le Quéré, M. R. Raupach, A. Sharifi, P. Smith and Y. Yamagata, *Nat. Clim. Change*, 2014, **4**, 850–853.
116 S. Kartha and K. Dooley, The risks of relying on tomorrow's negative emissions to guide today's mitigation action, 2016, Working Paper 2016–08, Stockholm Environment Institute. Retrieved 4 October, 2016 from https://www.sei-international.org/publications.
117 P. Smith, *Glob. Change Biol.*, 2016, **22**, 1315–1324.
118 T. B. Cochran, H. A. Feiveson, W. Patterson, G. Pshakin, M. Ramana, M. Schneider, T. Suzuki and F. von Hippel, *Fast Breeder Reactor Programs: History and Status*, International Panel on Fissile Materials, 2010.
119 OECD, *Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences*, OECD Publishing, Paris (France), 2019.
120 T. E. Graedel and J. Cao, *Proc. Natl. Acad. Sci. U. S. A.*, 2015, **112**(14), 4257–4262.
121 World Bank Database, World Bank database, 2019, http://data.worldbank.org/.
122 USGS, Mineral Commodity Summaries 2015, United States Geological Survey, 2015, https://minerals.usgs.gov/minerals/pubs/mcs/.
123 C. de Castro and I. Capellán-Pérez, *BioPhysical Economics and Resource Quality*, 2018, 3–14.
124 P. A. Prieto and C. A. S. Hall, *Spain's Photovoltaic Revolution: The Energy Return on Investment*, Springer, 2013th edn, 2013.
125 GWEC, Global Wind Report 2016, Global Wind Energy Council, 2017, http://gwec.net.
126 C. J. Barnhart and S. M. Benson, *Energy Environ. Sci.*, 2013, **6**, 1083–1092.
127 EC, Critical raw materials for the UE. Report of the Ad-hoc Working Group on defining critical raw materials, European Commission, 2010.
128 A. Elshkaki and T. E. Graedel, *J. Cleaner Prod.*, 2013, **59**, 260–273.
129 A. García-Olivares, J. Ballabrera-Poy, E. García-Ladona and A. Turiel, *Energy Policy*, 2012, **41**, 561–574.
130 T. Prior, D. Giurco, G. Mudd, L. Mason and J. Behrisch, *Glob. Environ. Change*, 2012, **22**, 577–587.
131 U. Bardi, *Extracted: How the Quest for Mineral Wealth Is Plundering the Planet*, Chelsea Green Publishing, White River Junction, Vermont, 2014.
132 T. E. Graedel, E. M. Harper, N. T. Nassar, P. Nuss and B. K. Reck, *Proc. Natl. Acad. Sci. U. S. A.*, 2015, **112**, 4257–4262.
133 G. M. Mudd, S. M. Jowitt and T. T. Werner, *Ore Geol. Rev.*, 2017, **86**, 924–938.
134 F. Ferroni and R. J. Hopkirk, *Energy Policy*, 2016, **94**, 336–344.
135 C. A. S. Hall, S. Balogh and D. J. R. Murphy, *Energies*, 2009, **2**, 25–47.
136 M. Raugei, S. Sgouridis, D. Murphy, V. Fthenakis, R. Frischknecht, C. Breyer, U. Bardi, C. Barnhart, A. Buckley, M. Carbajales-Dale, D. Csala, M. de Wild-Scholten, G. Heath, A. Jæger-Waldau, C. Jones, A. Keller, E. Leccisi, P. Mancarella, N. Pearsall, A. Siegel, W. Sinke and P. Stolz, *Energy Policy*, 2017, **102**, 377–384.
137 M. Raugei and E. Leccisi, *Energy Policy*, 2016, **90**, 46–59.
138 I. N. Kessides and D. C. Wade, *Sustainability*, 2011, **3**, 2339–2357.
139 C. Neumeyer and R. Goldston, *Sustainability*, 2016, **8**, 421.
140 D. J. Murphy, M. Carbajales-Dale and D. Moeller, *Energies*, 2016, **9**, 917.
141 C. W. King, J. P. Maxwell and A. Donovan, *Energies*, 2015, **8**, 12949–12974.
142 C. King, *An Integrated Biophysical and Economic Modeling Framework for Long-Term Sustainability Analysis*, Social Science Research Network, Rochester, NY, 2019.

143 IPCC, Special Report on Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press, UK and New York (USA), 2011.

144 V. Smil, *Energy Transitions: History, Requirements, Prospects*, Praeger, Santa Barbara, California, 2010.

145 G. Hammond and C. Jones, Inventory of Carbon & Energy (ICE) Version 2.0, Sustainable Energy Research Team (SERT) Department of Mechanical Engineering University of Bath, UK, 2011.

146 M. S. Masnadi and A. R. Brandt, *Energy Environ. Sci.*, 2017, **10**, 1493–1504.

147 N. Gagnon, C. A. S. Hall and L. Brinker, *Energies*, 2009, **2**, 490–503.

148 M. Dale, S. Krumdieck and P. Bodger, *Sustainability*, 2011, **3**, 1972–1985.

149 E. Dupont, R. Koppelaar and H. Jeanmart, *Appl. Energy*, 2018, **209**, 322–338.

150 E. Dupont, R. Koppelaar and H. Jeanmart, *Appl. Energy*, 2020, **257**, 113968.

151 G. Calvo, G. Mudd, A. Valero and A. Valero, *Resources*, 2016, **5**, 36.

152 J. H. M. Harmsen, A. L. Roes and M. K. Patel, *Energy*, 2013, **50**, 62–73.

153 G. M. Mudd, *Resour. Policy*, 2010, **35**, 98–115.

154 A. R. Brandt, *Biophys. Econ. Resour. Qual.*, 2017, **2**, 2.

155 A. García-Olivares, J. Solé and O. Osychenko, *Energy Convers. Manage.*, 2018, **158**, 266–285.

156 IEA, *Transport, energy and CO_2: moving toward sustainability,* International Energy Agency, Paris, 2009.

157 IEA ETP, *Energy Technology Perspectives 2016. Towards Sustainable Urban Energy Systems*, International Energy Agency, 2016.

158 S. Carrara and T. Longden, *Transportation Res. Part D: Transport Environ.*, 2017, **55**, 359–372.

159 A. J. Friedemann, *When trucks stop running: Energy and the future of transportation*, Springer, 2015.

160 IEA, *The Future of Trucks. Implications for Energy and the Environment*, OECD & IEA, 2017.

161 IEA, *Global EV Outlook 2016. Beyond one million electric cars*, OECD/IEA, Paris, 2016.

162 IEA, *The contribution of natural gas vehicles to sustainable transport*, OECD Publishing, 2010.

163 UNFCCC, *Paris Agreement*, 2015.

164 WEO, *World Energy Outlook 2014*, OECD/IEA, Paris, 2014.

165 I. de Blas, M. Mediavilla, I. Capellán-Pérez and C. Duce, Under review.

166 P. Kyle, P. Luckow, K. Calvin, W. Emanuel, N. Mayda and Y. Zhou, *GCAM 3.0 Agriculture and Land Use: Data Sources and Methods*, PNNL Technical Report, 2011.

167 E. Stehfest, D. van Vuuren, L. Bouwman, T. Kram, *et al.*, *Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications*, Netherlands Environmental Assessment Agency (PBL), 2014.

168 V. Smil, *Power Density: A Key to Understanding Energy Sources and Uses*, The MIT Press, Cambridge, Massachusetts, 2015.

169 J. Rockström, W. Steffen, K. Noone, Å. Persson, F. S. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen and J. A. Foley, *Nature*, 2009, **461**, 472–475.

170 M. Hejazi, J. Edmonds, L. Clarke, P. Kyle, E. Davies, V. Chaturvedi, M. Wise, P. Patel, J. Eom, K. Calvin, R. Moss and S. Kim, *Technol. Forecase. Soc.*, 2014, **81**, 205–226.

171 I. Arto, V. Andreoni and J. M. Rueda-Cantuche, *Water Resour. Econ.*, 2016, **15**, 1–14.

172 M. Meinshausen, S. Raper and T. Wigley, *Atmos. Chem. Phys.*, 2011, **11**, 1417–1456.

173 T. S. Fiddaman, *Feedback complexity in integrated climate-economy models*, Massachusetts Institute of Technology, 1997.

174 J. Goudriaan and P. Ketner, *Clim. Change*, 1984, **6**, 167–192.

175 H. Oeschger, U. Siegenthaler, U. Schotterer and A. Gugelmann, *Tellus*, 1975, **27**, 168–192.

176 R. W. Howarth, *Energy and Emission Control Technologies*, 2015, **3**, 45–54.

177 M. Burke, S. M. Hsiang and E. Miguel, *Nature*, 2015, **527**, 235–239.

178 UNFCCC, *Paris Agreement*, United Nations, Paris (France), 2015.

179 J. Hansen, M. Sato, P. Hearty, R. Ruedy, M. Kelley, V. Masson-Delmotte, G. Russell, G. Tselioudis, J. Cao, E. Rignot, I. Velicogna, B. Tormey, B. Donovan, E. Kandiano, K. von Schuckmann, P. Kharecha, A. N. Legrande, M. Bauer and K.-W. Lo, *Atmos. Chem. Phys.*, 2016, **16**, 3761–3812.

180 R. Knutti, J. Rogelj, J. Sedláček and E. M. Fischer, *Nat. Geosci.*, 2016, **9**, 13–18.

181 E. Kriegler, K. Riahi, N. Bauer, V. J. Schwanitz, N. Petermann, V. Bosetti, A. Marcucci, S. Otto, L. Paroussos, S. Rao-Skirbekk, T. A. Currás, S. Ashina, J. Bollen, J. Eom, M. Hamdi-Cherif, T. Longden, A. Kitous, A. Méjean, F. Sano, M. Schaeffer, K. Wada, P. Capros, D. P. van Vuuren, O. Edenhofer, C. Bertram, R. Bibas, J. Edmonds, N. Johnson, V. Krey, G. Luderer, D. McCollum and K. Jiang, *Technol. Forecase. Soc.*, 2015, **99**, 273–276.

182 J. C. V. Pezzey and P. J. Burke, *Ecol. Econ.*, 2014, **106**, 141–154.

183 G. Giraud, F. M. Isaac, E. Bovari and E. Zatsepina, *AFD Redearch Papers*, No. 2016-29, 2016.

184 C. Kousky, *Energy Econ.*, 2014, **46**, 576–592.

185 E. J. Moyer, M. D. Woolley, N. J. Matteson, M. J. Glotter and D. A. Weisbach, *J. Legal Stud.*, 2014, **43**, 401–425.

186 I. Capellán-Pérez and C. De Castro, Under review.

187 J. E. Stiglitz, A. Sen and J.-P. Fitoussi, Report by the Commission on the Measurement of Economic Performance and Social Progress, Commission on the Measurement of Economic Performance and Social Progress, Paris (France), 2010.

188 I. Arto, I. Capellán-Pérez, R. Lago, G. Bueno and R. Bermejo, *Energy Sustainable Dev.*, 2016, **33**, 1–13.

189 F. Cottrell, *Energy and society: the relation between energy, social changes, and economic development*, McGraw-Hill, 1955.

190 W. F. Lamb and J. K. Steinberger, *Wiley Interdiscip. Rev. Clim. Change*, 2017, **8**, e485.

191 J. Tainter, *The Collapse of Complex Societies*, Cambridge University Press, 1990.

192 L. A. White, *Am. Anthropol.*, 1943, **45**, 335–356.

193 UN, Report of the Inter-Agency and Expert Group on Sustainable Development Goal Indicators, United Nations. Economic and Social Council. Statistical Commission, 2015.

194 R. Costanza, I. Kubiszewski, E. Giovannini, H. Lovins, J. McGlade, K. E. Pickett, K. V. Ragnarsdóttir, D. Roberts, R. De Vogli and R. Wilkinson, *Nature*, 2014, **505**, 283–285.

195 I. Kubiszewski, R. Costanza, C. Franco, P. Lawn, J. Talberth, T. Jackson and C. Aylmer, *Ecol. Econ.*, 2013, **93**, 57–68.

196 J. Van den Bergh, *Abolishing GDP*, Social Science Research Network, Rochester, NY, 2007.

197 J. C. J. M. van den Bergh, *J. Econ. Psychol.*, 2009, **30**, 117–135.

198 B. C. O'Neill, E. Kriegler, K. L. Ebi, E. Kemp-Benedict, K. Riahi, D. S. Rothman, B. J. van Ruijven, D. P. van Vuuren, J. Birkmann, K. Kok, M. Levy and W. Solecki, *Glob. Environ. Change*, 2017, **42**, 169–180.

199 D. P. van Vuuren, M. T. J. Kok, B. Girod, P. L. Lucas and B. de Vries, *Glob. Environ. Change*, 2012, **22**, 884–895.

200 MEA, *Millennium Ecosystem Assessment. Ecosystems and Human Well-being: Scenarios*, Island Press, Washington DC (USA), 2005, vol. 2.

201 S. Kc and W. Lutz, *Glob. Environ. Change*, 2017, **42**, 181–192.

202 SSP db, *SSP Database (Shared Socioeconomic Pathways) - Version 1.1 (October 2016)*, 2016, available at: https://tntcat.iiasa.ac.at/SspDb.

203 M. Timmer, A. A. Erumban, R. Gouma, B. Los, U. Temurshoev, G. J. de Vries, I. Arto, V. A. A. Genty, F. Neuwahl, J. Francois, *et al.*, *The world input-output database (WIOD): contents, sources and methods*, Institue for International and Development Economics, 2012.

204 IEA ETP, Energy Technology Perspectives 2017. Catalysing Energy Technology Transformations, International Energy Agency, 2017.

205 IRENA db, *IRENA Resource*, International Renewable Energy Agency, 2019, http://resourceirena.irena.org.

206 SHC, *Solar Heat Worldwide. Markets and Contribution to the Energy Supply 2014*, Solar Heating & Cooling Programme IEA, 2016.

207 US EIA db, USA Energy Statistics, US Energy Information Administration, 2018, http://www.eia.gov.

208 M. Schneider and A. Froggatt, *The World Nuclear Industry Status Report 2017*, Mycle Schneider Consulting Project, Paris, London, Washington DC, 2017.

209 Bloomberg, *New Energy Outlook 2018*, New York (USA), 2018.

210 H.-H. Rogner, R. F. Aguilera, R. Bertani, S. C. Bhattacharya, M. B. Dusseault, L. Gagnon, H. Haberl, M. Hoogwijk, A. Johnson, M. L. Rogner, H. Wagner and V. Yakushev, in *Global Energy Assessment - Toward a Sustainable Future*, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012, pp. 423–512.

211 R. J. Brecha, *Energy Policy*, 2012, 51, 586–597.

212 J. D. Hughes, *Drill Baby Drill: Can Unconventional Fuels Usher in a New Era of Energy Abundance?*, CreateSpace Independent Publishing Platform, 1st edn, 2013.

213 J. Ritchie and H. Dowlatabadi, *Energy Econ.*, 2017, **65**, 16–31.

214 M. Z. Jacobson and M. A. Delucchi, *Energy Policy*, 2011, **39**, 1154–1169.

215 C. Kerschner and D. W. O'Neill, in *Sustainability. Key Issues*, ed. H. Kopnina and E. Shoreman-Ouimet, Routledge, 2016, p. 392.

216 M. Lenzen, *Energies*, 2010, **3**, 462–591.

217 F. Trainer, *Renewable energy cannot sustain a consumer society*, Springer Science & Business Media, 2007.

218 T. Kastner, M. J. I. Rivas, W. Koch and S. Nonhebel, *Proc. Natl. Acad. Sci. U. S. A.*, 2012, **109**, 6868–6872.

219 P. Smith, P. J. Gregory, D. van Vuuren, M. Obersteiner, P. Havlík, M. Rounsevell, J. Woods, E. Stehfest and J. Bellarby, *Philos. Trans. R. Soc., B*, 2010, **365**, 2941–2957.

220 T. Abbasi and S. A. Abbasi, *Crit. Rev. Environ. Sci. Technol.*, 2012, **42**, 99–154.

221 F. Danielsen, H. Beukema, N. D. Burgess, F. Parish, C. A. Brühl, P. F. Donald, D. Murdiyarso, B. Phalan, L. Reijnders, M. Struebig and E. B. Fitzherbert, *Conservat. Biol.*, 2009, **23**, 348–358.

222 D. W. Keith, J. F. DeCarolis, D. C. Denkenberger, D. H. Lenschow, S. L. Malyshev, S. Pacala and P. J. Rasch, *Proc. Natl. Acad. Sci. U. S. A.*, 2004, **101**, 16115–16120.

223 L. Miller, F. Gans and A. Kleidon, *Earth Syst. Dynam.*, 2011, **2**, 1–12.

224 L. M. Miller and D. W. Keith, *Joule*, 2018, **2**, 2618–2632.

225 R. R. Hernandez, M. K. Hoffacker, M. L. Murphy-Mariscal, G. C. Wu and M. F. Allen, *Proc. Natl. Acad. Sci. U. S. A.*, 2015, 201517656.

226 P. Moriarty and D. Honnery, *Renewable Sustainable Energy Rev.*, 2012, **16**, 244–252.

227 M. Giampietro and K. Mayumi, *The biofuel delusion: The fallacy of large scale agro-biofuels production*, Routledge, 2009.

228 H. Barnett and C. Morse, *Scarcity and Growth. The Economics of Natural Resource Availability*, John Hopkins Press, Balitmore, 1963.

229 A. C. Fisher, in *Scarcity and growth reconsidered*, ed. V. K. Smith, Johns Hopkins University Press, Baltimore, MD, 1979, pp. 249–275.

230 C. J. Cleveland, *Ecological Economics: The Science and Management of Sustainability*, 1991, pp. 289–317.

231 T. S. Lontzek, Y. Cai, K. L. Judd and T. M. Lenton, *Nat. Clim. Change*, 2015, **5**, 441–444.

232 NAS, *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*, National Academies Press, 2017.

233 IPCC, Global Warming of 1.5 °C, Intergovernmental Panel on Climate Change (IPCC), 2018, http://www.ipcc.ch/report/sr15/.
234 D. Acemoglu, *Introduction to Modern Economic Growth*, Princeton University Press, Princetown, NJ, 2008.
235 P. Aghion and P. W. Howitt, *The Economics of Growth*, MIT Press, Cambridge, Massachusetts & London, England, 2008.
236 M. Dale, S. Krumdieck and P. Bodger, *Ecol. Econ.*, 2012, **73**, 152–157.
237 UNEP, *Recycling rates of metals. A status report*, International Resource Panel. United Nations Environment Programme, 2011.
238 RCP db, RCP Database (version 2.0), 2009, available at: https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=welcome.
239 J. W. Lund and T. L. Boyd, *Proceedings World Geothermal Congress 2015*, Melbourne, Australia, 2015, p. 31.
240 BP, *BP Statistical Review of World Energy June 2016*, British Petroleum, 2016.
241 FAOSTAT, *Statistics Division of the FAO*, Food and Agriculture Organization of the United Nations, Rome (Italy), 2019.
242 T. Crownshaw, C. Morgan, A. Adams, M. Sers, N. Britto dos Santos, A. Damiano, L. Gilbert, G. Yahya Haage and D. Horen Greenford, *Anthropocene Rev.*, 2018, 2053019618820350.
243 R. Fernández Durán and L. González Reyes, *En la espiral de la energía*, Libros en Acción, 2nd edn, 2018, https://www.ecologistasenaccion.org/?p=29055.
244 Y. Xu and V. Ramanathan, *Proc. Natl. Acad. Sci. U. S. A.*, 2017, **114**, 10315–10323.
245 R. U. Ayres, J. C. J. M. van den Bergh, D. Lindenberger and B. Warr, *Struct. Change Econ. Dynam.*, 2013, **27**, 79–88.
246 J. Hickel and G. Kallis, *New Polit. Econ.*, 2019, 1–18.
247 G. Carrington and J. Stephenson, *Energy Res. Soc. Sci.*, 2018, **46**, 103–113.
248 D. H. Meadows, J. Randers and D. L. Meadows, *The limits to growth: the 30-year update*, Chelsea Green Publishing Company, White River Junction, Vt, 2004.
249 G. M. Turner, *Glob. Environ. Change*, 2008, **18**, 397–411.
250 G. Turner, *Global Collapse Imminent?*, Melbourne Sustainable Society Institute, The University of Melbourne, 2014.
251 C. T. M. Clack, S. A. Qvist, J. Apt, M. Bazilian, A. R. Brandt, K. Caldeira, S. J. Davis, V. Diakov, M. A. Handschy, P. D. H. Hines, P. Jaramillo, D. M. Kammen, J. C. S. Long, M. G. Morgan, A. Reed, V. Sivaram, J. Sweeney, G. R. Tynan, D. G. Victor, J. P. Weyant and J. F. Whitacre, *Proc. Natl. Acad. Sci. U. S. A.*, 2017, **114**, 6722–6727.
252 F. Gotzens, H. Heinrichs, J.-F. Hake and H.-J. Allelein, *Energy Strategy Rev.*, 2018, **21**, 71–81.
253 IEA, *World Energy Outlook 2017*, OECD/IEA, Paris, 2017.
254 IEA and IRENA, *Perspectives for the Energy Transition. Investment Needs for a Low-Carbon Energy System*, International Energy Agency and International Renewable Energy Agency, 2017.
255 M. Z. Jacobson, M. A. Delucchi, G. Bazouin, Z. A. Bauer, C. C. Heavey, E. Fisher, S. B. Morris, D. J. Piekutowski, T. A. Vencill and T. W. Yeskoo, *Energy Environ. Sci.*, 2015, **8**, 2093–2117.
256 NREL, *Renewable Electricity Futures Study (Entire Report)*, National Renewable Energy Laboratory, Golden, CO, USA, 2012.
257 G. Limpens and H. Jeanmart, *Energy*, 2018, **152**, 960–973.
258 G. Palmer, *Energies*, 2018, **11**, 839.
259 E. Zenzey, *State of the World 2013: Is sustainability still possible?* Worldwatch Institute, Washington, Island Press, 2013, pp. 73–83.
260 P. P. Christensen, *Ecol. Econ.*, 1989, **1**, 17–36.
261 S. D'Alessandro, T. Luzzati and M. Morroni, *J. Cleaner Prod.*, 2010, **18**, 291–298.
262 D. I. Stern, *Ecol. Econ.*, 1997, **21**, 197–215.
263 N. Georgescu-Roegen, *World Dev.*, 1975, **3**, 765–783.
264 D. E. James, H. M. A. Jansen and J. B. Opschoor, *Economic Approaches to Environmental Problems*, Elsevier North Holland, Amsterdam, 1978.
265 T. Uehara, Y. Nagase and W. Wakeland, *Systems Science Faculty Publications and Presentations*, 2013.
266 *Input-Output Economics*, ed. W. Leontief, Oxford University Press, Oxford, New York, 2nd edn, 1986.
267 W. Leontief, *Rev. Econ. Statist.*, 1970, **52**, 262–271.
268 R. S. J. Tol, *Rev. Environ. Econ. Policy*, 2018, **12**, 4–25.
269 Y. Dafermos and C. Papatheodorou, *Int. Rev. Appl. Econ.*, 2015, **29**, 787–815.
270 E. Daudey and C. García-Peñalosa, *J. Dev. Stud.*, 2007, **43**, 812–829.
271 J. Fargione, J. Hill, D. Tilman, S. Polasky and P. Hawthorne, *Science*, 2008, **319**, 1235–1238.
272 H. Haberl, D. Sprinz, M. Bonazountas, P. Cocco, Y. Desaubies, M. Henze, O. Hertel, R. K. Johnson, U. Kastrup, P. Laconte, E. Lange, P. Novak, J. Paavola, A. Reenberg, S. van den Hove, T. Vermeire, P. Wadhams and T. Searchinger, *Energy Policy*, 2012, **45**, 18–23.
273 D. Pimentel, A. Marklein, M. A. Toth, M. N. Karpoff, G. S. Paul, R. McCormack, J. Kyriazis and T. Krueger, *Hum. Ecol.*, 2009, **37**, 1–12.
274 T. Searchinger, R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes and T.-H. Yu, *Science*, 2008, **319**, 1238–1240.