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The limits of transport decarbonization under the current growth paradigm

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A R T I C L E I N F O

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A B S T R A C T

Achieving ambitious reductions in greenhouse gases (GHG) is particularly challenging for transportation due to the technical limitations of replacing oil-based fuels. We apply the integrated assessment model MEDEAS-World to study four global transportation decarbonization strategies for 2050. The results show that a massive replacement of oil-fueled individual vehicles to electric ones alone cannot deliver GHG reductions consistent with climate stabilization and could result in the scarcity of some key minerals, such as lithium and magnesium. In addition, energy-economy feedbacks within an economic growth system create a rebound effect that counters the benefits of substitution. The only strategy that can achieve the objectives globally follows the Degrowth paradigm, combining a quick and radical shift to lighter electric vehicles and non-motorized modes with a drastic reduction in total transportation demand.

1. Introduction

The transition to a non-carbon society is a major source of concern among researchers interested in achieving sustainable societies. Decarbonization efforts are motivated by the need to reduce greenhouse gas emissions (GHGs) and avoid worst-case climate change scenarios, as well as anticipate the depletion of fossil fuels. In this context, transportation is routinely identified as one of the most difficult sectors to decarbonize. This is due to current cultural mobility patterns, the fact that transport is the least diversified energy end-use sector, the continuous growth of global demand for mobility, and the technical limitations to replacing oil-based fuels [1–5]. Emissions increased by 2.5% annually between 2010 and 2015, and over the past half century the sector has witnessed faster emissions growth than any other [2].

Today, transportation largely relies on liquid fuels (95%) (mainly derived from oil) and 55% of the world's total liquid fuels are dedicated to this end [6]. It is also a key sector, essential for powering trade and most industrial processes and services, including industrial agriculture for food production [7]. The lack of energy for transportation is expected to have an impact on all the other sectors, especially in a strongly globalized economy. GHG emissions related to transport are continuously rising in most countries; in spite of more efficient vehicles (road, rail, water and aircraft) and the adoption of better policies. The IPCC has found that, following current trends, GHG emissions from transport could increase at a faster rate than emissions from the other energy end-use sectors, reaching around 12 Gt CO2eq/yr by 2050 [8].

Adapting to the depletion of oil (and especially that of high quality) is a key motivation to decarbonize transportation, although not so publicly recognized. The estimations of the decline in global peak oil dates and rates vary among authors in the literature [9–17]. Most global oil extraction forecasts predict stagnation in 2020s decade. Although there are some uncertainties related to the amount of non-conventional oil that can be exploited, there is much consensus on the decline in conventional oil, while the historical data from 2006 onwards show that the production of conventional oil is already stagnated [18–21].

Complying with those restrictions requires a drastic fall in fossil fuel consumption and, accordingly, in GHG emissions from now to the middle of the century, as the IPCC scenarios propose [8,22].

Two main technical reasons complicate reducing the environmental footprint of current transportation. On the one hand, much of the global vehicle market is already covered by highly optimized fuel-economy standards, so further improvements are difficult [23]. Furthermore, not even current official standards are met in real performance; as shown by the *Dieselgate* scandal [24] and misstatements of fuel economy in the US and Japan. It was demonstrated that when the vehicle' computer software would detect that it was being tested, the engine would be commanded to run below normal power and performance, hence emitting less emissions. In fact, the analysis of real-world performance shows that efficiency has remained virtually unchanged since 2010, despite the political and regulatory pressure to reduce emissions [23]. On the other hand, the substitutes for oil-based fuels in transport are

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Abbreviations

BAU	Business as usual
BEV	Battery electric vehicles
CCS	Carbon capture and sequestration
CEV	Catenary electric vehicles
CHV	Catenary hybrid vehicles
CNG	Compressed natural gas
CSP	Concentrated solar power
CTL	Coal to liquids
EOL	End-of-lifetime
EROI	Energy return on energy investment
EV	Electric vehicles
GDP	Gross domestic product
GDPpc	Gross domestic product per capita
GHG	Greenhouse gases
GTL	Gas to liquids
HV	Heavy vehicles
IAM	Integrated assessment model
ICE	Internal combustion engines
iLUC	indirect land use change
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LV	Light vehicles
MEDEAS-W	MEDEAS-World
PV	Photovoltaic
RES	Renewable energy sources
TEV	Tracked electric vehicle
WIOD	World Input Output Database

technically inferior and are limited by biophysical constraints and thermodynamic limits (see section 2).

However, the difficulties of the transition are not only technical; the dynamics derived from the interaction between the energy, the technology and the economy are crucial aspects of the decarbonization process. That is why the energy transition forecast is frequently based on models, such as Integrated Assessment Models (IAMs). IAMs aim to link the main features of society and the economy with the biosphere and atmosphere into one modeling framework [25]. Equality is another important dimension, more difficult to be captured by IAMs, e.g., data for the UK show that ~70% of flights are taken by 15% of the population, while at least half of the population take no flights at all in each year, three quarters of this air travel is by members of the middle and upper social classes [26].

Conventional mitigation strategies in the transportation sector focus on supply-side vehicle technology efficiency gains and fuel switching, especially for light-duty personal vehicles (see group (1) in Table 1, see Appendix 1 for an expanded description of the literature review). These options face several challenges, as many aspired technological changes require major infrastructure changes and investments, and are not commercially available today and their large-scale economical availability in the future is subject to critical uncertainties (e.g., fuel cells, advanced biofuels). For example, Yeh et al. [27] study the transportation energy use and emissions of four global transportation models with considerable technological detail (GCAM, MESSAGE-Transport, MoMo and Roadmap) in the 2050 horizon. These results base their reduction in emissions on policies that assume no mobility reduction and strong increases in technical efficiencies. The estimated efficiencies in Yeh et al. [27] fall below 100gCO_2/km, far lower than the efficiency that Tietge et al. [23] estimated as the stagnated current value based on real data (167gCO_2/km). Carrara and Longden [28] studied the future of freight transportation based on the WITCH model. Their results show that road freight decarbonization options are limited and the current dominance of internal combustion engine trucks may only decline by the middle of the century. Van der Zwaan et al. [29] used the TIAM-ECN model, finding that the transport sector is more costly and difficult to decarbonize than others (such as electricity production or industry). Their scenarios of high growth in transportation, CCS technologies and hydrogen-fueled cars are, however, highly uncertain; given that these technologies are not currently available, nor demonstrated or commercial, while they also imply a significant worsening of the efficiency of the energy system if they are scaled up [30,31]. Karkatsoulis et al. [32], used the GEM-E3T model to simulate CO2 emission reduction in transport in the EU (80% liquid fuels reduction in passenger cars). They found that the replacement of conventional internal combustion vehicles (ICE) vehicles by electric ones could have positive effects on the EU economy, despite the higher costs. This analysis offers an interesting perspective as it addresses the impact on the economic sectors. Yet, it does not check whether such high deployment of advanced biofuels and electric cars, to which their results are acknowledged to be substantially sensitive, are economically viable at large-scale and feasible in an international context of limited fertile land and minerals [33–36]. Nor does it check whether advanced biofuels are net carbon sources due to land use change emissions [37–40]. All of the above studies find that the decarbonization of the transportation sector is possible only under the assumption that future currently uncertain technologies such as CCS, hydrogen, fuel cells, etc. are massively available commercially and at a sustainable level. Those scenarios which are more realistic manage only to avoid the additional environmental impacts of additional demand, but not decreasing the impacts in absolute terms (see Table 1 and Appendix 1). Moreover, mitigation studies in transportation sector are heavily skewed towards passenger transportation, freight options being understudied [8,41].

In this context, an increasing body of research is pointing to the fact that, without strong behavioural changes, the sustainability crisis will not be solved, which is particularly valid for the case of transportation [42,44,52,53]. For example, Girod et al., 2013 [49] developed a specific transportation model and found a combination of travel behaviour changes (more walking, cycling and train travel) which stabilizes GHG emissions from transport at current levels. Van de Ven et al. [50] implemented in the IAM GCAM model of a suite of behavioural policies which do not require any personal up-front investment affecting different sectors including mobility. Van Sluisveld et al. [51] simulated lifestyle changes in the transport sector within the IAM IMAGE, which allow an additional reduction in GHG of ~10% relative to the scenario to be obtained, considering solely technological mitigation options. McCollum et al. [3] extended the Van Sluisveld et al. [51], methodology to represent heterogeneous consumer preferences in multiple global energy-economy models, specifically focusing on the non-financial preferences of individuals. They found that strategies and policies explicitly targeting consumer preferences towards alternative fuel vehicles are needed to drive the widespread adoption of these advanced technologies. Still, despite lifestyle changes have in theory a great potential for reducing energy consumption and GHG in the transportation sector, to date model implementations are scarce and have not fully tested the most radical options proposed in the literature to avoid such as living car-free, shifting massively to very light vehicles such as e-bikes or reducing drastically demand, especially in the most polluting modes such as aviation [42,45,46,52] (see groups (2) and (3) in Table 1 and Appendix 1). Moreover, few of these studies, excepting García-Olivares et al. [31], contemplate limits in the availability of minerals for the transition to a sustainable mobility.

In this paper we focus on several strategies to decarbonize the global transportation sector by 2050 comparing the conventional efficiency

Table 1
Overview of relevant works including results of GHG emissions' reductions in the sector Transport considering (1) mainly technological changes, (2) mainly lifestyle changes of citizens and (3) combining citizens' lifestyle and technological changes. We follow here the definition of citizens' lifestyle changes proposed by Van den Berg et al. [42] based on the ASI framework (avoid, shift, improve), in which only "*avoid*" and "*shift*" are considered lifestyle changes while "*improve*" features such as efficiency improvements and technological substitutions when providing the same output but using a different set of inputs are not.

Measures analyzed	Methodology	Results	References
(1) GHG mitigation in transportation applying mainly technological change options. Focus on light-duty vehicles choice: efficiency improvements, replacement of conventional ICE vehicles by alternative fuels (electric, hybrid, fuel cell, biofuels, etc.)	Simulation forecast models	Decarbonization possible only under the assumption that future currently uncertain technologies such as CCS, hydrogen, fuel cells, etc. are massively available commercially and at a sustainable level. Those scenarios more realistic manage only to avoid the additional environmental impacts of additional demand, but not decreasing the impacts in absolute terms.	[3,27–29,32,43]
(2) GHG mitigation in transportation focusing on citizens' lifestyle change options. Modal shift (public transport, biking, etc.), auto maintenance, driving behaviour, carpooling, living car-free, reducing air travel, telework, etc.	Literature review	Lifestyle changes have in theory a great potential for reducing energy consumption and GHG but to date model implementations are scarce and have not tested the most radical options	[42,44–46]
	Literature review + static analysis		[47,48]
	Simulation forecast models		[49–51]
(3) GHG mitigation in transportation combining citizens' lifestyle and technological change options	Literature review	The combination of lifestyle changes with technological changes provides the most promising results. This is a novel field of research with scarce studies where again the most radical options have barely been tested.	[5,52]
	Literature review + static analysis		[31]
	Simulation forecast models		[53–56]

improvement and technological substitution scenarios with a scenario including drastic changes in the mobility patterns which are deemed to be necessary by the aforementioned studies [42,45,46,52], and which can be representative of an interpretation of global Degrowth transportation scenario, which to the best of our knowledge has not been tested in a quantitative framework [44]. To this aim, we apply the system dynamics IAM MEDEAS-W [57,58], which presents the particularity of incorporating an economic model combining input-output analysis with a post-Keynesian approach linked to a detailed energy-technology model of renewable and non-renewable energy sources that contemplates limits of fossil fuel flows, minerals and land requirements. MEDEAS-W is a model incorporating such aspects as the inertia of the socioeconomic system and delays in the adoption of new technologies, including feedback relations between the energy and the economy, relations that are frequently ignored in other climate change and energy transition studies [59] (see section 3).

The structure of the paper is as follows: Section 2 describes the main aspects and numbers of the energy transition in transportation; Section 3 briefly describes the MEDEAS-W model; Section 4 analyses the present objective of decarbonization and peak oil adaptation. Section 5 proposes a set of scenarios that show some critical aspects of the energy transition in transportation. Finally, the results, discussion and conclusions are given in Sections 6, 7 and 8.

2. Technical aspects of the energy transition in transportation

The easiest substitutes for oil-based liquid fuels in transportation are those that do not require a substantial change in current vehicles: biofuels, natural gas (Compressed Natural Gas, CNG; Liquefied Natural Gas, LNG and Liquefied Petroleum Gas, LPG), and liquid fuels produced from coal (coal-to-liquids) or natural gas (gas-to-liquids). Electrical and hybrid vehicles require a costlier change in vehicles and charging infrastructures. Public transportation, railways and changes in mobility patterns have great energy saving potentials, but require profound behaviour change, as well as heavy investments and changes in infrastructures. Other proposed alternatives, such as hydrogen fuel cell vehicles, have an uncertain potential.

2.1. Renewable fuels

Doubt has been cast on biofuels as a sustainable, global alternative to oil in transportation. This is because, given their low power density, very large areas of land would have to be used to cover a significant share of the global vehicles. This would critically affect other dimensions, such as biodiversity or food production [52,60–62]. On the other hand, there is also evidence that present biofuels are responsible for indirect land use change (iLUC), whose emissions are of the same magnitude order as combustion emissions of fossil fuels [37,39,40,63].

Second generation biofuels are based on cellulosic material from plants, which could be grown without competing with crops, or coming from crop residues and other organic waste. However, their scaling faces challenges related to low efficiency (despite further improvements being expected), soil fertility and nutrients loss, soil carbon sink potential, etc. [38,64–68]. In particular, the loss of fertile soils worldwide makes some authors defend the incorporation of forest and human residues for composting rather than for energy use [38]. A similar argument can be applied to biogas [69].

Another alternative could be the use of "renewable" methane to power internal combustion engines as García-Olivares et al., studied in their work [31]. In fact, natural gas could be obtained sustainably from fermentation of farm and urban wastes and by combining electrolytic H_2 with CO_2 in the Sabatier process. On the one hand, the fermentation of farm and urban wastes are limited by aforementioned factors. On the other hand, the Sabatier process depends on the viability of the full cycle of hydrogen generation and transport, and in order to be sustainable would require that the CO_2 is either captured from the air, or from fuel combustion, technologies which are today also subject to large uncertainties.

2.2. Fossil fuels other than oil

Natural gas vehicles (CNG and LPG for small vehicles and LNG for trucks due to its higher volumetric density) today comprise 3% of the light vehicles in use in the world and a growing number of heavy vehicles, but they are not considered in this study as a valid alternative to decarbonization in the long run because they depend on a non-renewable fossil fuel [12,17,70,71]. Despite the emissions associated to their combustion being slightly lower than those of other fossil fuels, producing less atmospheric pollution; their GHG emissions throughout the entire lifecycle (including methane leakages in the extraction and transportation processes) are similar to those of gasoline and diesel [20,72–77]. Moreover, their use of energy is similar: according to FTF [66] and Hekkert et al., [78].

Coal-to-liquids (CTL) and gas-to-liquids (GTL) refer to the transformation of coal and natural gas into liquid hydrocarbons and have carbon emissions similar to or greater than those of oil-based liquid fuels [79]. Therefore, although they might alleviate the peak oil restriction, they are not a valid alternative for decarbonization. Moreover, all existing technologies are characterized by low efficiencies, between 27 and 50% [80–82], and their current global production is exiguous [83].

2.3. Electric vehicles and fuel cells

Diverse types of electric vehicles can replace the use of liquid fuels: battery electric, plug-in and non-plug-in hybrid vehicles. Non-plug-in hybrid cars have higher efficiencies than conventional cars, but they are basically vehicles powered by liquid fuels. The average savings that hybrid vehicles achieve can be approximated by comparing the fuel performance of a Toyota Prius (4.3 L gasoline/100 Km) with the average consumption of similar gasoline cars (6 l/100 Km), which means a ~33% saving (van Mierlo et al. [84] estimate a similar value).

In terms of battery size and electricity consumption, which are the most relevant aspects to our model, plug-in hybrids are more similar to pure electric vehicles than non-plug-in hybrids (average of 10 KWh battery for plug-in hybrids compared to 20 KWh of Battery Electric Vehicles (BEV) and 1.9 KWh of non-plug-in hybrids). The tank-to-wheel energy use of BEV is three times less final energy than those of the liquid fuel equivalent vehicle [85], and they have already obtained a modest share in the market (a fleet of 5 million vehicles out of the more than 1300 million private cars in the world).

Battery electric vehicles are the best option for private electric transportation in terms of energy saving and potential GHG emission reduction due to vehicle use [65]. However, it should be borne in mind that, in the whole life cycle analysis, the differences between battery electric and gasoline vehicles are smaller. In terms of total GHG emissions, EEA2018 estimates an approximately 20% lower normalized climate change impact for electric vehicles, while the impact on water and land toxicity doubles that of liquid-powered vehicles [86,87].

The substitution of liquid fuels in transportation becomes more complex when the vehicles are heavier and need to travel long distances, as is the case for long-haul heavy trucks. This is mainly due to thermodynamic limits to the energy density that electric batteries can store in chemical form, while keeping an acceptable reversible capacity able to deliver a sufficient number of recharging cycles [88,89]. In addition, current electric trucks such as the Man e-truck [90] have a maximum range of up to 200 km and weight around 15 tones. If the range of e-trucks were to be increased to 800 km to compete with conventional trucks, they would need much heavier batteries than the allowed weight for trucks with loads in the EU today. This means that, despite technological improvements being expected in the future, future electric batteries will have an energy density that will not be sufficient to carry large loads over long distances. In fact, this practical limit will likely be around one magnitude order below the energy density of oil [91].

This is the key reason why the automobile industry is replacing heavy materials in conventional vehicles by lighter alternatives. For example, steel components of the electric motor, battery and vehicle body may be replaced by other metals, such as wrought aluminum, magnesium and titanium, or composite materials such as carbon fiber reinforced plastic (CFRP). On the other hand, these materials tend to require more energy and have a higher global warming potential in the production stage than the heavier materials they replace [92–94].

Many technologies have been proposed as alternative to conventional ICE trucks such as electric batteries (for hybrid or purely electric vehicles, including battery-swapping options), diverse options of road electrification (CHV/CEV, Catenary Electric/Hybrid vehicles; TEV, Tracked Electric Vehicle), fuel cell electric vehicles as well as modal shift to electric rail [8,28,31,41,95–99]. Both battery-swapping and the electrification of roads requires the development of commercial routes connected to the grid with high power lines, either through regular battery-swap stations allowing for fast charging or through full electrification of the road (either through overhead catenary, ground conductive or inductive solutions). CHV has been estimated to yield similar emissions levels than BEV [95]. Road electrification for freight poses challenges in terms of planning of commercial routes between transport and logistic companies, a coordinated strategy between the different states cut across these commercial routes, reduced flexibility for loading and delivery, and requires very large monetary investments (similar or even higher to rail electrification [97]). Battery-swapping slows the journey and also increases the required number of batteries in the system, which may be a relevant constraint in the future given their dependence on critical minerals (although some trade-offs exist given that a smaller battery allows for higher truck loads). Similar challenges exist for the modal shift of freight to rail with two key differences: (1) this option is in place and commercially viable for decades in many countries, and (2) it is a much more energy efficient technology which makes that emissions increases due to shifting passenger and freight activity to rail are more than an order of magnitude lower than those displaced from other modes [41]. This high efficiency is due to the design of the railway directed to achieve constant speeds which combined with the lower friction in rails allows a locomotive to transport much higher loads with the same energy than heavy trucks. In fact, different reports conclude that a certain level of shift to electric rail is necessary to reduce the GHG emissions of transportation in line with the Paris Agreement [41,96]. However, to maintain the current flexible system a high level of inter-modality between rail and road will be required in the future [41,96].

A fuel cell vehicle is one which uses a fuel cell instead of a battery, or in combination with a battery or supercapacitor, to power its on-board electric motor. Fuel cells in vehicles generate electricity to power the motor, generally using oxygen from the air and compressed hydrogen. Hydrogen can be synthetized from electricity, although currently it is typically reformed from natural gas. Their overall efficiency is much lower than that of other options: overall efficiencies for cars that use synthetic liquid fuel from electricity are only 13% (from electricity to wheel), while the efficiency for battery electric vehicles is 69% and for hydrogen fuel cell vehicles 26% [30]. For electrofuels to be viable, the challenge is not simply technological learning, but access to a low-cost ultra-low-carbon electric power system, or to low-carbon electric generators with high annual availability [100].

We consider that the electrification of aviation, marine transportation and heavy vehicles is not a plausible option in the time frame of this analysis [28,31,54,97,101,102]. The exceptions are hybrid heavy trucks [97] (although with a very reduced saving ratio with relation to ICE vehicles given that most of the journey is performed at relatively constant speed with limited possibilities for regenerative braking [98,103]) and electric buses, which are in fact already in the public transport system of some cities, but with a tank-to-wheel efficiency ratio of 0.5, significantly lower than that of light cars [104].

3. Methodology

3.1. Overview of the MEDEAS-W model

The MEDEAS family of models is a set of policy-simulation dynamic-recursive System Dynamics models developed with the aim of informing decision-making in order to achieve the transition to sustainable energy systems with a focus on biophysical, economic, social and technological restrictions, while also tackling some of the limitations identified in the current IAMs [57,58]. The models typically run from 1995 to 2050, although the simulation horizon may be extended to 2100 when focusing on long-term strategic sustainability analyses. MEDEAS-W in particular is the global-aggregated (1 region) version, and is structured in nine main modules: Economy, Energy demand, Energy availability, Energy infrastructures & EROI, Minerals, Land-use, Water, Climate/Emissions, and Social & Environmental impact indicators. The main characteristics of each module are:

- **Economy:** the global economy in MEDEAS is modeled assuming non-clearing markets (i.e., not forcing general equilibrium), demand-led growth and complementarity instead of perfect substitutability. Hence, production is determined by final demand and economic structure, combined with such supply-side constraints as energy availability. The economic structure is captured by the adaptation and dynamic integration of global WIOD input-output tables, resulting in 35 industries and 4 institutional sectors [59,105].
- **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 [106].
- **Energy availability**: this module includes the potential and availability of renewable and non-renewable energy resources, taking into account biophysical and temporal constraints. The modeling of energy availability is mainly based on the previous model WoLiM [15]. In particular, the availability of non-renewable energy resources depends on both stock and flow constraints [9,12,107]. In total, 25 energy sources and technologies and 5 final fuels are considered (electricity, heat, solids, gases and liquids), with large technological disaggregation. The model can be considered partially hybrid, combining top-down and bottom-up approaches for diverse sectors (see section 3.2). The intermittency of renewable energy sources (RES) is considered in the framework in a stylized way, computing endogenous levels of overcapacities, storage and additional transmission grids, depending on the penetration of variable RES technologies (see Supplementary information in Refs. [33]).
- **Energy infrastructures & EROI**: this is the representation of the capacities for generating electricity and heat, considering planning and construction delays. The energy investments for renewable energies 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 [33]. The variation in the EROI of the system affects the energy demand. Transportation is modeled in great detail, differentiating between different types of vehicles for households, as well as freight and passenger inland transport. See section 3.2 for a detailed description of the modeling of transportation in MEDEAS.
- **Minerals:** minerals are required by the economy, with emphasis on those needed for the construction and maintenance of alternative energy technologies. Recycling policies are available.
- **Land-use:** this module mainly accounts for the land requirements of the RES energies.
- **Water:** this module allows water use to be calculated by type (blue, green and grey) by economic sector and for households.
- **Climate:** this module projects the climate change levels due to GHG emissions generated by human societies (non-CO2 emissions are exogenously set, taking RCPs scenarios as reference [108]). The carbon and climate cycle is adapted from C-ROADS [109,110]. This module includes a damage function that translates increasing climate change levels into damage to human systems.
- **Social and environmental impacts:** this module translates the "biophysical" results of the simulations into metrics related to social and environmental impacts. The objective is to contextualize the implications for human societies in terms of well-being for each simulation.

The modules have different levels of development; the most detailed ones being the Economy, Climate and those related to energy. The modules concerning Minerals, Land-use and Water are more stylized representations focused on computing the social and environmental impacts that, nevertheless, do not feedback to the rest of the system. Most of the variables of the model run on a yearly basis, although in order to capture some specific shorter dynamics for which data is available, the model runs on a shorter time-step ($0.03125 \cdot 365 = 11.68$ days).

In this paper, the MEDEAS-W_v1_4_33 model version is used[1] A schematic overview of these modules can be seen in Fig. 1.

One of the main features distinguishing MEDEAS-W from other IAMs is the fact that it does not assume continuous economic growth. MEDEAS-W is rather based on the principles of biophysical and ecological economics, which assume that the availability of final energy acts as a limiting factor of the economic process. The energy intensities (defined as the ratio of the final energy spent by every economic sector divided by the economic output of that sector) evolve over time due to technological progress. In addition, the shortage of each type of final energy stimulates the inter-final energy replacement; however, if these substitutions are not sufficient, the economic process is restricted to the amount of final energy available [59]. 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) [111,112]. This energy-economy feedback is described in Fig. 1 (*Energy scarcity feedback*).

The impacts of climate change are also fed back into the economy in the standard version of the model by using damage functions that are driven by temperature change levels (*Climate change damages* in Fig. 1). However, in this article, the climatic feedback has been deactivated in order to see the dynamics of the transition in the transportation sector with more clarity. More information on the climatic feedback of MEDEAS-W can be found at Capellán-Pérez & de Castro [113].

Mineral availability is also contemplated in the framework. The demand for minerals in RES technologies & electric vehicle batteries is calculated, for each key aspect, by choosing a representative technology, avoiding those most affected by the scarcest minerals. A stylized approach is applied to estimate the consumption of minerals by the rest of the economy, given the close relationship between economic activity and mineral consumption in the current socio-economic industrial system. MEDEAS-W compares the total primary demand for minerals to be extracted from the mines (after accounting for recycling rates RC, in recycled content) with the estimated level of their geological availability (reserves and resources). This way an estimation of mineral scarcity is computed, but it does not constrain economic activities (contrary to the case of energy scarcity) due to much lower robustness of the demand estimation as well as on the data on mineral availability [33].

3.2. Modeling of transportation in the MEDEAS-World model

Transportation is modeled in great detail in MEDEAS-W, enabling the simulation of bottom-up transition policies based on the replacement of liquid-fuel vehicles by other types of vehicles and fuel, as well as the possibility of a modal shift to light electric vehicles and demand-management policies. These bottom-up policies are applied to households and inland transportation together with the endogenous evolution of households and inland sector economic demand. So, households and inland sector follow a hybrid approach. For air and water transportation, bottom-up policies are not considered, since the use of fuels other than liquids in those sectors does not seem to be a viable option in the future due to technical and thermodynamic limitations [31,54,91,102]. For these sectors, as well as for the other sectors of the economy, the standard top-down energy intensity improvement is considered (see section

[1] The latest versions of the models are freely available at: https://www.medeas.eu/model/medeas-model. Future updates of the models will be available at: http://geeds.eu/.

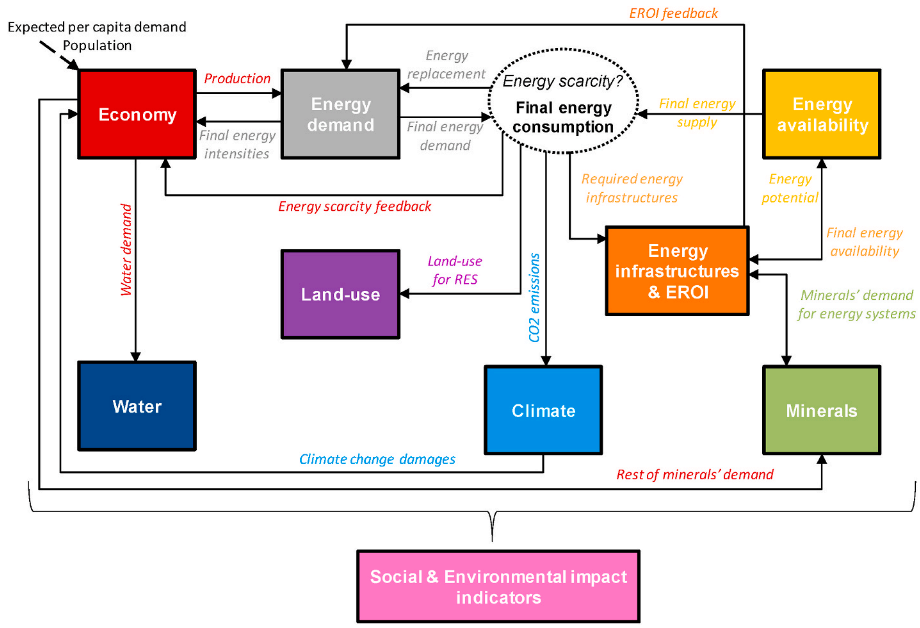

Fig. 1. MEDEAS-World model schematic overview. The main variables connecting the different modules are represented in italics and by solid arrows. The dashed arrow represents the exogenous driver inputs. EROI: Energy return on energy investment. RES: renewable energy sources. Source: adaptation from Refs. [58].

3.2.2).

3.2.1. Bottom-up policies based on vehicle & fuel replacements (households and inland transportation)

Because of all the drawbacks described in section 2, liquid biofuels and biogas are not considered as a relevant alternative for the bottom-up policy and they are modeled in the energy subsector of MEDEAS-W as a source of liquid fuels subject to a sustainable maximum potential. The limit is set (according to the MEDEAS-W BAU scenario), at 6.8 Mboe/day for biofuels (more than three times the current consumption) and 2.4 Mboe/day for biogas (which amounts to 10% of the current consumption of liquids, around 95 Mboe/day). Liquids obtained from gas (GTL) and coal (CTL) are subject to the availability determined in the model by the demand of other uses.

The types of vehicle and fuel modeled in MEDEAS-W for household transport bottom-up policies are the following: four-wheelers of liquid fuels, electric, hybrid and natural gas; and electric and liquid fuel-based two-wheelers. The category electric encompasses purely battery electric vehicles and plug-in hybrids, since they are more similar in terms of battery size and use of electricity than non-plug-in hybrids.

The vehicles considered for the Inland Transportation sector are: light duty vehicles of the same categories as household four wheelers; liquid fuels, gas fuel and hybrid vehicles are considered for heavy vehicles; liquid fuels, gas fuel, electric and hybrid vehicles for buses; and trains powered by liquids and electricity.

The user can set policy targets in terms of shares of every type of vehicle and fuel in a target year. The model translates these shares into changes in the corresponding final energy intensities of Households (e_hh) and Inland Transportation (linear time evolution) using the derivative of the intensities, as shown in eq. (1) for the case of two- and four-wheelers powered by liquids in households:

$$\frac{d\,e\_hh_{liq}}{d\,t}=\frac{d}{dt}\left(\frac{fed\_hh_{liq}}{hh}\right)=\frac{d}{dt}\left(\frac{H\cdot\%H_{liq4w}\cdot use_{H4w}\cdot EF_{liq4w}}{hh}\right)+\frac{d}{dt}\left(\frac{H\cdot\%H_{hyb4w}\cdot use_{H4w}\cdot EF_{hyb4w}}{hh}\right)+\frac{d}{dt}\left(\frac{H\cdot\%H_{liq2w}\cdot use_{H2w}\cdot EF_{liq2w}}{hh}\right) \tag{1}$$

H being the total number of household vehicles in 2015, fed_hh the final energy demand of housholds, hh the households economic demand, $\%H_{liq4w}, \%H_{hyb4w}, \%H_{liq2w}$ the share of liquid four-wheelers, hybrid four-wheelers and liquid two-wheelers; use_{H4w}, use_{H2w} the average use of four-wheel and two-wheel vehicles in terms of Km/year/vehicle in 2015 and $EF_{liq4w}, EF_{hyb4w}, EF_{liq2w}$ the technical efficiencies of vehicles expressed in energy per Km.

By default, it is assumed that the mobility patterns are maintained, since such modal shifts as widespread public transportation or demand management options reducing total transport demand require deep cultural changes and are today far from the scenarios assumed by international agencies. However, MEDEAS-W also represents potential modal shifts such as the possibility of replacing four-wheelers by electric bikes, mopeds and non-motorized transport in cities. Hence, the number and use of vehicles divided by household demand is assumed to be a constant from 2015 values (see constants A1 and A2 in eq. (2)).

$$A1=\left(\frac{H\cdot use_{H4w}\cdot EF_{liq4w}}{hh}\right);A2=\left(\frac{H\cdot use_{H2w}\cdot EF_{liq2w}}{hh}\right) \tag{2}$$

expressing the variation of the intensity as (eq. (3)):

$$\frac{d\,e\_hh_{liq}}{d\,t}=A1\frac{d}{dt}\%H_{liq4w}+A1\cdot sr_{hyb}\cdot\frac{d}{dt}\%H_{hyb4w}+A2\cdot\frac{d}{dt}\%H_{liq2w} \tag{3}$$

Technical efficiencies are relative to the efficiency of liquid vehicles using saving ratios (sr_k). They are assumed to be 0.66 for hybrid cars [114], 0.95 for hybrid heavy vehicles [98,103], 1 for gas vehicles [31, 78], 0.33 for electric four- and two-wheelers [85], 0.5 for electric buses

[104] and 0.6 for electric trains [114]. For the rest of vehicles, the same efficiency is assumed with relation to liquid vehicles.

The same approach is used for other final energies and Inland Transportation vehicles.

3.2.2. Top-down policies based on energy intensity (air and water transportation)

The estimation of energy demand in MEDEAS-W in the top-down framework is performed through a method based on projecting energy intensities [106]. Based on historical data, the energy intensities of the economic sectors (e_{ik}) by sector i and by final energy k (solids, liquids, gases, electricity and heat)(eq. (4)), and the households energy intensity () by final energy k (eq. (5))e_{hhk} are calculated.

$$e_{ik} = \frac{fed_{ik}}{x_i} \tag{4}$$

$$e_{hhk} = \frac{fed_{hhk}}{hh} \tag{5}$$

where fed_{ik} is the final energy demand by sector i and by final energy k and fed_{hhk} is the final energy demand of households by final energy k.

These historical energy intensities are extrapolated into the future and the estimated intensities are used to calculate the future energy demand. Thus, by multiplying the energy intensities of industries and households by the sectoral production (x_i) and household demand (hh) respectively, the estimation of the total final energy demand is obtained by the final energy $tfed_k$.

The historical and extrapolated evolution of air and water transportation sectors energy intensities can be seen in Fig. 2.

3.2.3. Modeling of the restructuration of production as a result of the change in demand

Demand-driven policies imply a restructuration of the production of the various sectors. For example: if private cars are replaced by e-bikes, the economic sectors related to vehicle manufacturing and maintenance must undergo a contraction, since the new vehicles require a much lower economic activity to be manufactured and maintained. If the replacement of private cars is done by non-motorized means such as walking, the production related to the replaced vehicles disappears entirely. The input-output framework allows the implications of this structural change to be captured for the whole economy. The coupling with the rest of the MEDEAS model allows the associated change in energy use and emissions to be computed.

These demand-driven policies are at present developed in MEDEAS-W for the aforementioned bottom-up policies of substitution of four-wheelers by electric bikes, mopeds and non-motorized transport. The user can choose a percentage of the households' four-wheelers to be substituted by very light electric vehicles, such as e-bikes or mopeds as well as by non-motorized means. Taking the share of replaced four-wheelers as reference, the economic activity of the sectors "Transport Equipment" and "Sale Maintenance and Repair of Motor Vehicles and Motorcycles Retail Sale of fuel" is reduced accordingly. These changes are implemented as follows in the input-output framework (see eq. (6) and eq. (7)): $\overline{fd}$ and $\overline{x}$ represent respectively the final demand and production initially, while $\overline{fd}$' and $\overline{x}$' represent the final demand and production after the effects of the replacement are considered. For the sake of simplicity, the Leontief Inverse Matrix $(I\text{-}A)^{-1}$, representing the relative interdependencies between sectors, is assumed to remain constant in this analysis.

$$\overline{x} = (I - \boldsymbol{A})^{-1} * \overline{fd} \tag{6}$$

$$\overline{x}' = (I - \boldsymbol{A})^{-1} * \overline{fd}' \tag{7}$$

The reduction of economic activity in these sectors is estimated through two steps:

- The identification of the share of the added value (which corresponds to final demand in the IO framework) corresponding to cars in these sectors. According to Eurostat data for the EU-27 based on the NACE code [115], 72% of the added value of the sector "Transport Equipment" and 98% for "Sale Maintenance and Repair of Motor Vehicles and Motorcycles Retail Sale of fuel" correspond to cars. These numbers are taken as reference in this study since, to the best of the authors' knowledge, there is a lack of global data.

- Identification of the reduction in the supplied final demand when replacing cars with very light vehicles and non-motorized modes. As reference, we have taken standard price and the average occupancy rate for each mode. Therefore, the replacement of each car by very light vehicles corresponds to the reduction of the economic demand in these sectors of (1-$red\_veh_{j,i}$) (see eq. (8)). $red\_veh = 0$ for walking and, for the sake of simplicity, is also assumed to be 0 for non-electric biking, given the relatively cheap price of this type of bikes that run on manpower.

$$red\_veh_{j,i} = \frac{price_i}{price_j} * \frac{occupancy\ rate_j}{occupancy\ rate_i} \tag{8}$$

where j is the substituted vehicles (cars) and i the substitutes (e-bikes, mopeds, non-motorized). The average price of a car is estimated at 30,000 € [116], mopeds at 4000 € [117,118] and e-bikes at 2000 € [117, 118]. The average car occupancy rate is assumed to be 1.5, motorcycle 1.2 [119–121] and e-bike 1. This means that the replacement of one four-wheeler by one e-bike would reduce the demand of the "Transport Equipment" and "Sale Maintenance and Repair of Motor Vehicles and Motorcycles Retail Sale of fuel" sectors by 90%; and one four-wheeler by one motorcycle by 84%.

Eq. (9) shows the overall change in final demand after accounting for: (1) the reduction in the demand of the two transport related' economic sectors mentioned above due to the replacement of cars by very light vehicles and non-motorized modes (see eq. 10), and (2) the increase in the demand of the rest of sectors as a result of the re-spending of the income saved in the two aforementioned sectors (see eq. (11)).

$$\overline{fd}' = \begin{pmatrix} fd_1 + ECO_{inc} \\ fd_2 + ECO_{inc} \\ \dots \\ fd_{t.eq} * ECO_{red} \\ \dots \\ fd_{t.sa} * ECO_{red} \\ \dots \\ fd_{34} + ECO_{inc} \\ fd_{35} + ECO_{inc} \end{pmatrix} \tag{9}$$

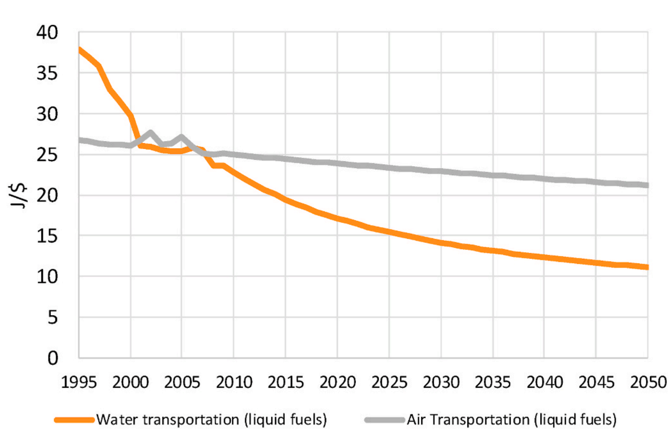

Fig. 2. Projection of final energy intensities (J/$) of the transport sectors in MEDEAS-World. (Dollars correspond to 1995US $). Historical data are from the WIOD database [105] up to 2009.

$$ECO_{red} = 1 - \left(\%sub_{car,mop} * \left(1 - red_veh_{car,mop}\right) + \%sub_{car,ebikes} * \left(1 - red_veh_{car,ebikes}\right) + \%sub_{car,nonmot}\right) \tag{10}$$

$$ECO_{inc,\ i} = \left(fd_{trans.eq} - fd'_{trans.eq}\right) + \left(fd_{sale.trans} - fd'_{sale.trans}\right) * \frac{fd_i}{\left(tfd - fd_{trans.eq} - fd_{sale.trans}\right)} \tag{11}$$

In eq. (9), $f\acute{d}'$ is the demand after the replacement, $fd_{1\ \ldots\ 35}$ is the original economic demand (with indexes from 1 to 35 corresponding with the 35 WIOD sectors with the exceptions of "t.eq" and "t.sa" which correspond with the sectors 19 ("Transport Equipment") and 20 ("Sale Maintenance and Repair of Motor Vehicles and Motorcycles Retail Sale of fuel"), respectively, which have been renamed in eq. (9) for the sake of clarity). ECO_{red} is the share of economic final demand reduction in these transport related sectors, and ECO_{inc} is the increase in the economic final demand after the distribution of the re-spent income in the rest of sectors.

In eq. (10) $\%sub_{car,mop}$, $\%sub_{car,ebikes}$ and $\%sub_{car,nonmot}$ are the shares of substitution of cars by mopeds, e-bikes and non-motorized.

In eq. (11), tfd is the total final demand, and i represents the rest of the sectors.

Note also that these different transport modes are not perfect substitutes, given that four-wheelers allow the transport of people who may not be autonomous, carry loads, are faster, etc. In the real world, these alternative options are complementary. However, we assume that within a Degrowth paradigm shift, the effect of substitution between these modes would dominate over the effect of complementarity; which is not what is currently happening for example with the electric cars.

3.2.4. Mineral requirements of electrical batteries

The number of batteries needed for these electric vehicles is calculated in MEDEAS-W assuming that all vehicle batteries are of the type $LiMn_2O_4$. The choice of a representative technology simplifies the process of integrating different technologies in the model (although at the cost of disregarding potential substitutions among sub-technologies). $LiMn_2O_4$ electric vehicle batteries were selected given that, although they are less efficient than other alternatives (e.g., $LiCoO_2$), they require a substantially lower embodied energy for their fabrication [122,123], thus making them more attractive in terms of net energy analysis [33]. Previous literature has found that both cobalt and manganese could face supply bottlenecks to fulfill future battery demand [36,124]. However, Mn can be considered a more abundant mineral, given that the estimated reserves are 2 orders of magnitude higher than those of Co and the requirements per battery for both metals are of the same magnitude order [125,126].

An average value of energy stored of 21.3 KWh for purely electric cars batteries is assumed taking as reference the Nissan Leaf EV [123]. Hybrid vehicles need much smaller batteries, and the overview of the main hybrid models in Refs. [127] shows an average battery for hybrid light vehicles of 1.43 KWh. Heavy vehicles and buses require larger batteries, while two wheelers required substantially smaller ones. The battery mass for different electric transportation modes is estimated taking the light electric vehicle as a reference and comparing it with the average weight of the different electric transportation vehicles from Sanz et al. [114], as shown in Table 2.

The materials included in $LiMn_2O_4$ electric batteries correspond to those reported by Ref. [123,128,129] for the Nissan Leaf EV (see Table 3). Moreover, the demand of 19 critical minerals from the whole economy is calculated in MEDEAS-W. Data for resources and reserves are taken from different sources [126,130–133]. Generally, the term "resources" is used to represent the amount of mineral (proven or geologically possible) that cannot currently be exploited for technical and/or economic reasons, but which may be exploitable in the future. "Reserves" refer to the fraction of the resource base estimated to be economically extractable at the time of determination.

Modeled mineral recycling rates correspond to the share of recycled content (RC) in the fabricated metal. Current recycling rates in MEDEAS are taken in general from UNEP [134]. However, for the case of lithium, the UNEP reference (reporting <1%) seems to be outdated. Taking as reference the data from Melin [135], which found that almost 100,000 lithium-ion batteries were recycled in 2018, mainly in China and South Korea which represent almost the 90% of the lithium recycling world market, amounting to around half of the total lithium-ion batteries reaching the end-of-lifetime (EOL) that year globally, and considering that hydrometallurgical combined with pyrolysis and/or mechanic processes as a pre-step is the most used recycling method of these batteries in both countries (which allows to achieve a 57% maximum recycling efficiency of lithium [136–139]), while in the rest of the world other less performant methods such as pyrolysis which does not recover any lithium are more common, and assuming a 85% efficiency in the recycling process due to lower efficiency of industrial processes vs laboratory conditions, we find that global current lithium EOL recycling rate could be ~21%. Assuming a current annual global growth of lithium batteries reaching EOL of ~35%/year, this would correspond to ~15% RC recycling content nowadays. The impact of recycling on primary production is assumed, for the sake of simplicity, to be one-to-one displacement. However, in reality, reprocessing generally entails material and quality losses. On the other hand, we do not consider that some materials, such as composites, may also be more difficult to recycle, increasing the impact of end-of-life processes and necessitating

Table 2
Ratios of battery mass (kg) for different electric transportation modes relative to purely light electric vehicles. LV: Light Vehicle. "-" represents combinations of vehicle type and fuel not modeled in MEDEAS (see text for justification).

	Electric	Hybrid
Household LV	1	0.10
Cargo LV	1.52	0.15
Heavy Vehicles (HV)	–	0.83
Buses	9.8	0.65
Two wheelers	0.078	–
E-bikes	0.03	–

Table 3
Material intensity of Li batteries $LiMn_2O_4$. The charged battery delivers 21.3 kWh which would allow to cover 117 km. Assuming a lifetime of 10 years, 2000 cycles (equivalent to almost 150,000 km for a battery of 80 kW and 210 kg of weight (i.e. 12.5 batteries per MW). Source: own estimation from Refs. [123,128,129].

	Kg/MW
Aluminium	500
Copper	289
Lithium	34.4
Manganese	509.4
Rest (plastics, graphite/carbon, steel, electronics, P and F)	780

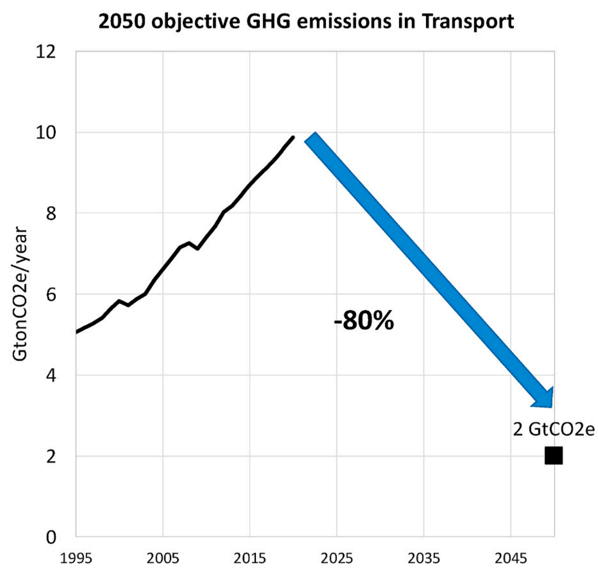

Fig. 3. Global GHG emissions reduction objective of −80% with relation to current levels in the Transportation sector targeted in this work by 2050.

the use of virgin raw materials over recycled ones in future products [94].

4. The objective of decarbonizing the global transportation system and the oil availability constraint

This paper explores the implications of different strategies to strongly decarbonize the global transportation system by 2050. For the objective of the decarbonization of the transportation system, we take as reference the estimated emissions reductions consistent with 1.5–2 °C long-term pathways as reported by the recent IPCC SR1.5 [2]. This report found that for limiting global warming below 1.5 and 2 °C, net zero emissions should be attained globally at around 2050 and 2070, respectively. Acknowledging that transport sector faces more complexities for its decarbonization than other sectors such as electricity or buildings [8] we set a −80% objective by 2050 compared to emissions in 2020, assuming that other economic sectors would need to make an additional mitigation effort during this period to be as close as possible from the 1.5 °C target (see Fig. 3).

Note that MEDEAS implicitly incorporates other biophysical constraints, such as the limitation of oil-derived fuels due to geological depletion over the next few decades; which is particularly relevant for transportation, given its current massive dependence on this resource (~95%). Here, we take the estimation of global oil extraction from J. Laherrère [140], a senior geologist who has been analyzing the depletion of oil and gas for decades and whose estimates have been pretty consistent over time [58,107]. This peak oil limitation, in the MEDEAS-W model, is assumed to be an external physical constraint on the economic activity. If the oil demanded by the economy is higher than the maximum extraction, inter-fuel substitution is triggered; however, if this substitution is not sufficient to cover the gap between demand and physical extraction, the economic activity is then limited by the available energy. The same modeling is applied to other non-renewable resources.

Note that these two limitations are different. GHG reduction is a desired objective that may or may not be achieved, depending on the specification of each scenario. The peak oil restriction is assumed to be an external limitation that cannot be overcome, since the economic activities are restricted in the MEDEAS-W model when liquids (or any other final energy) shortage appears [106]. In any case, in terms of scenario design, it is desirable that both energy consumption and GHG emissions should be below their limits, in order to avoid energy limitations on the economy (see the Results section).

5. Scenarios

Four scenarios are simulated with the MEDEAS-W model to analyze the main dynamics of the decarbonization of global transportation. All four scenarios focus on the transportation sector, and the rest of the model follows a BAU narrative, which is an extrapolation of observed trends (see the main parameters in Appendix 2). In this work, climate change impacts are deactivated for reasons of clarity. Table 4 collates the input assumptions for each scenario. The four simulated scenarios are:

- **Expected EV trends:** This scenario projects current and expected trends. The target percentage of each type of vehicle in 2050 is determined by the observed trends (see Appendix 3), which is the reference for the inputs in all scenarios. The historical data of the number of vehicles are taken from the IEA and the OICA [102,141,142], the forecasts to 2030 from the IEA [143,144] and the number of buses from Façanha et al., [145]. The number of current hybrid vehicles is roughly estimated from the sales of the main manufacturers, two-wheeler data come from the IEA [146], and natural gas vehicles from IANGV [147]. The number of current locomotives is obtained from IEA and Garcia-Olivares et al., [31,96].

The targets of light duty vehicles and buses are set the same as household vehicles. Hybrid and gas heavy vehicles have a negligible target percentage, since this is a scenario of present trends and their growth in this decade has been practically zero. Train targets maintain current levels.

- **EV High:** This is a hypothetical scenario of very high electrification in inland transportation. By 2050, all personal cars, buses and motorbikes are assumed to have been replaced by battery electrical vehicles and 80% of the heavy vehicles to be hybrid. This scenario does not pretend to be realistic, but serves as an example of extreme electrification with no changes in the cultural patterns of transportation.
- **E-bike:** This is another hypothetical scenario where governments take measures to promote a mobility based on very light electrical vehicles. This policy may be motivated by a diversity of reasons, such as avoiding the dependence on critical potentially scarce minerals, such as lithium, and to reduce problems inherent to the model of private mobility that generates problems of public space occupation, traffic jams, traffic-related accidents, segregation of spaces or the requirement of large communication roads. In this scenario, most personal cars are assumed to be replaced by electric 2 wheelers (60%), followed by e-bikes (20%) and non-motorized modes (8% of cars substituted and added to present amount of non-motorized trips). Only 12% of the household vehicles are similar to today's four-wheelers, but cargo vehicles remain based on liquid fuels because of the constraints to generalizing heavy batteries on a large scale. The shift to lighter vehicles has a feedback effect on the economic sectors related to vehicle manufacturing and maintenance, since smaller and simpler vehicles mean lower revenues for these industries. A modal shift of ICE heavy trucks to electric rail of 30% is assumed, so the share of freight transportation activity covered by electric rail increases from current 30%–60% by 2050.

Table 4
Scenario inputs and assumptions (targets correspond to the year 2050).

			Present (2015)	Expected EV trends	EV High	E-bike	Degrowth
Household vehicles	4-wheelers	liquids 4w	65.00%	15.00%	0.00%	2.20%	2.20%
		electric 4w	0.50%	35.00%	66.00%	9.60%	9.60%
		hybrid 4w	0.10%	10.00%	0.00%	0.10%	0.10%
		gas 4w	1.20%	6.00%	0.00%	0.10%	0.10%
	2-wheelers	liquids 2w	23.70%	6.80%	0.00%	0.00%	0.00%
		electric 2w	9.50%	27.20%	34.00%	60.00%	60.00%
	Additional substitutes	e-bikes	0.00%	0.00%	0.00%	20.00%	20.00%
		Non-motorized	0.00%	0.00%	0.00%	8.00%	8.00%
Inland transport heavy vehicles		liquids HV	99.80%	99.80%	20.00%	98.00%	98.00%
		hybrid HV	0.10%	0.10%	80.00%	1.00%	1.00%
		gas HV	0.10%	0.10%	0.00%	1.00%	1.00%
Inland transport light vehicles		liquids LV	98.90%	23.00%	0.00%	18.00%	18.00%
		electric LV	0.10%	53.00%	100.00%	80.00%	80.00%
		hybrid LV	0.10%	15.00%	0.00%	1.00%	1.00%
		gas LV	0.90%	9.00%	0.00%	1.00%	1.00%
Buses		liquids buses	100.00%	23.00%	0.00%	19.00%	19.00%
		electric buses	0.00%	53.00%	100.00%	40.00%	40.00%
		hybrid buses	0.00%	15.00%	0.00%	40.00%	40.00%
		gas buses	0.00%	9.00%	0.00%	1.00%	1.00%
Trains		liquids train	50.00%	50.00%	0.00%	0.00%	0.00%
		electric train	50.00%	50.00%	100.00%	100.00%	100.00%
Modal shift HV to train (pct. increase in trains)				0.00%	0.00%	30.00%	30.00%
			Present (2015)	**Expected EV trends**	**EV High**	**E-bike**	**Degrowth**
Recycling rate (RC) of minerals		Aluminium (Al)	35.00%	35.00%	70.00%	70.00%	70.00%
		Copper (Cu)	28.50%	28.50%	57.00%	57.00%	57.00%
		Lithium (Li)	15.00%	15.00%	30.00%	30.00%	30.00%
		Manganese (Mn)	37.00%	37.00%	74.00%	74.00%	74.00%
			Historical trends (1979–2014)	**Expected EV trends**	**EV High**	**E-bike**	**Degrowth**
GDPpc planned			1.4%/yr	1.4%/yr	1.4%/yr	1.4%/yr	Steady-state economy at 5000 1995 US$ per capita. (current 6500 1995 US$)
Household demand-management (pct vs 2020 Households demand)		Inland transport	NO	NO	NO	NO	−60.00%
		Water transport					−60.00%
		Air transport					−85.00%

- **Degrowth:** This is a customized scenario that fulfills the targets of decarbonization and peak oil adaptation through a reduction in the total transportation demand combined with vehicle shifts that mimic behavioural change. The shares of vehicles are the same as in the E-bike scenario, but assuming that the transportation demand of households is strongly reduced, due to a deep change in the cultural mobility patterns (average reduction of 60% for inland and water transport, and 85% for aviation vs 2020 households demand). As in the e-bike scenario, modal shift of ICE heavy trucks to electric rail of 30% is assumed, so the share of freight transportation activity covered by electric rail increases from current 30%–60% by 2050. This scenario assumes the context of a future where serious and co-ordinated efforts are taken to change the present growth-oriented economy towards one that fulfills human needs without the necessity for continuous growth, such as the one defended by the Degrowth movement [148–150]. This scenario, instead of pursuing continuous economic growth, targets a steady-state economy of 5000 1995 US$ average per capita by 2050 vs the current 6500 1995 US$.

A doubling of the estimated current recycling rates (in recycled content, RC) is assumed to be achieved during the period of simulation 2020–2050 in the 3 scenarios EV high, E-bike and Degrowth: 70% for

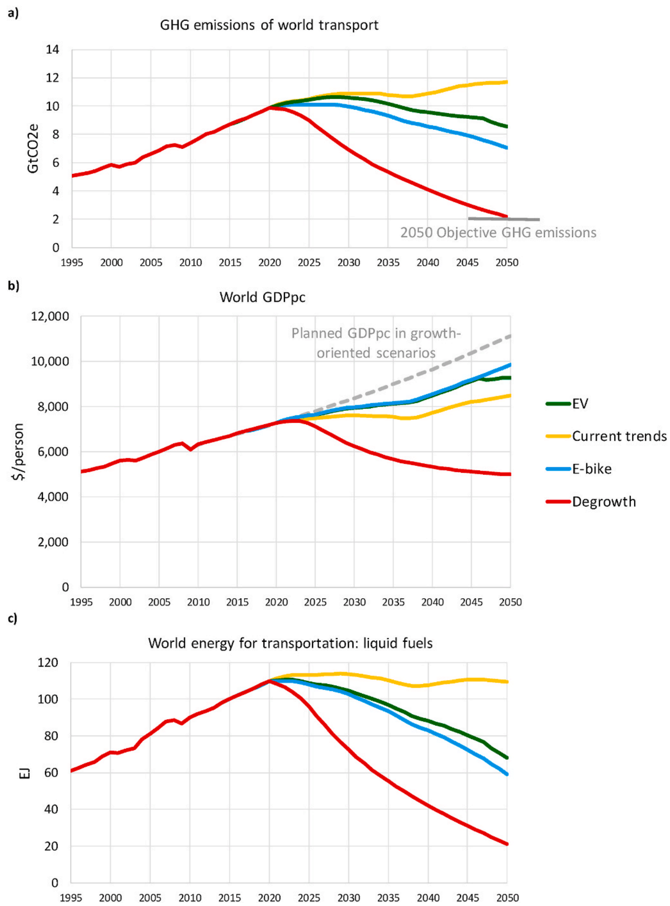

Fig. 4. a) World GHG emissions related to global transportation by scenario (GtCO2e/year), including direct transport emissions and the indirect emissions related to electricity production allocated to transport demand. The 2050 world GHG emissions reduction objective is 2 $GtCO_2e$ (see section 4). b) World GDPpc evolution by scenario. Planned GDPpc in growth-oriented scenarios is represented by grey dotted lines. (Dollars correspond to 1995US $). c) World liquid fuels consumption for transportation by scenario (EJ).

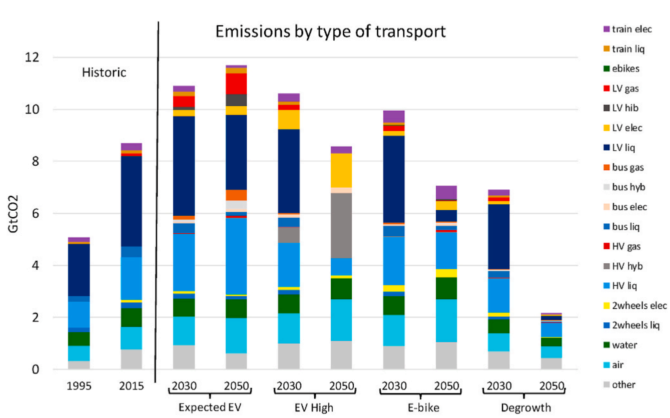

Fig. 5. World transportation emissions by type of transport in the four scenarios analyzed. LV = Light vehicles; HV= Heavy vehicles. LV aggregates Households 4 wheelers and inland transport light vehicles.

aluminum, 57% for copper, 30% for lithium and 74% for manganese. Although higher mineral recovery rates could be achieved in a context of proper incentives [151], the high growth levels of batteries reaching EOL difficult the recycling industry to cope with the increasing amounts of disposal to process.

The main assumptions for the four scenarios are shown in Table 4.

6. Results

The GHG emissions and energy consumption of global transportation and the global GDPpc and mineral consumption of the 4 scenarios described in the previous section are shown in the figures and tables below.

Fig. 4a shows that, in the Expected EV trends scenario, the global emissions of transportation grow to around 12 $GtCO_2e$ in 2050 (+20% growth from current levels). In the EV High and E-bike scenarios, the ambitious mitigation measures allow to reduce the GHG emissions of transportation by 2050 with relation to current levels despite the greater economic growth achieved than in the Expected EV scenario (see Fig. 4b). However, transport GHG emissions in both EV High and E-bike scenarios in 2050 are far from being 80% lower than in 2020 (15% and 30% reduction, respectively). The reasons for this are mainly three: the low electrification of air, water and freight transportation due to technical limits as discussed in Section 2 (see Fig. 5), the continuous increase in demand for transportation driven by economic growth and the increased share of unconventional fossil fuel in the energy mix as conventional fuels are depleted. Only Degrowth scenario reaches the objective of an 80% GHG reduction in transportation by 2050. It is important to highlight that the emissions related to electricity for EVs are obtained by assuming, in the model, a more ambitious hypothesis for renewable energy than the current trends. In these scenarios, renewable electricity in 2050 reaches 90%.

As shown in Fig. 4a, the GHG emissions of global transportation evolve very differently in the scenarios analyzed in this work. To better understand the evolution of GHG emissions over time, Fig. 5 shows the part of the emissions are due to each mode of transport and fuel used. The consumption of liquids for LV (dark blue) currently generates a large part of the CO_2 emissions of global transportation (around 40% of total emissions), the same occurs in the Expected EV scenario where substitutes of liquid fuels play a reduced role. In the other scenarios, the weight of GHG emissions from liquid LV on total emissions is reduced as they are progressively replaced by electric LV (orange) in the EV High scenario or 2 wheelers, e-bikes and non-motorized vehicles in E-Bike and Degrowth scenarios.

Fig. 5 also shows the importance of road freight transport (HV) in the total emissions of transportation. Liquid HV (light blue) generate around 20% of total GHG emissions in the historical period (1.87 $GtCO_2e$ in 2020) and in the Expected EV scenario HV increase to around 3 $GtCO_2e$ in 2050 (more than 25% total transport emissions). In the EV High scenario, liquid HV are replaced by hybrid HV, but HV still generate more than 3$GtCO_2e$ in 2050 (30% of total emissions). This is due to the fact that the energy savings of hybrid HV with relation to ICE vehicles, as reviewed in section 2, are very modest. However, the shift from liquids-based road to electrified rail freight transport has a significant impact on total emissions reduction. In the E-Bike and Degrowth scenarios the HV emissions in 2050 decrease compared to 2020 (20% in HV High and 65% in Degrowth scenario) and the electric trains (purple) generate very low emissions (0.5 $GtCO_2e$ in the EV High and 0.1 $GtCO_2e$ in the Degrowth scenario).

Last but not least, Fig. 5 shows the weight of aviation (turquoise blue) and maritime (green) transport in total transportation emissions. Both types of transport generate around 10% of the global emissions, and as explained in section 3, they evolve following a top-down approach projecting past energy efficiency trends as shown in Fig. 2. As reviewed in Section 2, the authors of this work do not foresee viable alternative technological options for the decarbonization of water and

Table 5
Ratio of global cumulated primary extraction of aluminum, copper, lithium and manganese from mines versus global reserves and resources by 2050. Bold numbers indicate >100%.

	Expected EV trends	EV High	E-bike	Degrowth
With relation to reserves				
Aluminum in 2050 for EV batteries	3.36%	2.75%	2.32%	1.93%
Aluminum in 2050 all uses	12.1%	9.60%	9.22%	7.55%
Copper in 2050 for EV batteries	37.1%	38.7%	28.0%	22.3%
Copper in 2050 all uses	**130.8%**	**118.4%**	**108.1%**	89.2%
Lithium in 2050 for EV batteries	58.9%	**132.8%**	38.9%	21.5%
Lithium in 2050 all uses	65.4%	**139.2%**	44.8%	26.1%
Manganese in 2050 for EV batteries	18.2%	25.5%	9.72%	6.10%
Manganese in 2050 all uses	**143.3%**	**120.6%**	**105.4%**	84.3%
With relation to resources				
Aluminum in 2050 for EV batteries	1.26%	1.03%	0.87%	0.72%
Aluminum in 2050 all uses	4.52%	3.36%	3.44%	2.81%
Copper in 2050 for EV batteries	12.7%	13.3%	9.59%	7.66%
Copper in 2050 all uses	44.9%	40.6%	37.1%	30.6%
Lithium in 2050 for EV batteries	20.1%	45.4%	13.3%	7.4%
Lithium in 2050 all uses	22.4%	47.6%	15.3%	8.9%
Manganese in 2050 for EV batteries	10.1%	14.1%	5.38%	3.38%
Manganese in 2050 all uses	79.3%	66.8%	58.3%	46.6%

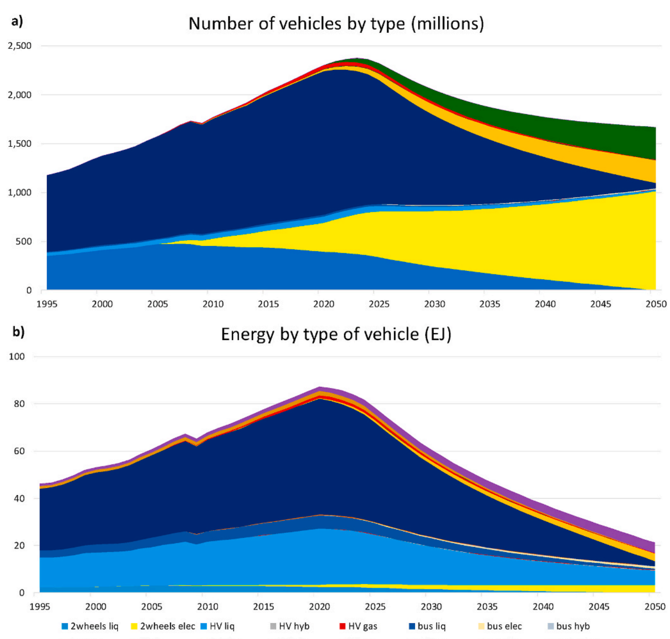

Fig. 6. a) Evolution of the number of vehicles for inland transportation by type in Degrowth scenario. b) Evolution of the energy consumption for inland transportation by type in Degrowth scenario. LV = Light vehicles; HV= Heavy vehicles. LV aggregates Households 4 wheelers and inland transport light vehicles.

air transport. In 2050 the weight of these modes in EV High and E-bike scenarios versus total emissions increases by almost 20% in the case of aviation and 13% for water, since on the one hand the planned ΔGDPpc and therefore the demand for these modes of transport increases over time in these scenarios (Fig. 4b) and on the other hand the emissions from other modes of transport decrease as energy-saving technologies and behaviors replace current liquids-based ICE vehicles.

In the growth-oriented scenarios, we find a period of stagnation due to peak oil limits at around 2025–2040 (Fig. 4b). In the EV High and E-bike scenarios, as the consumption of liquids for transportation is lower (Fig. 4c), the peak oil limitation is less severe and the GDP continues to grow (though, with approximately 1% growth, lower than the planned 1.4% annual growth in line with the historic global trends of +1.42% per year (1979–2014) [57]). This result is also remarkable, since it shows how important the transportation sector is for the whole economy in terms of the energy transition. In the scenarios explored in the paper, the transportation and electricity sectors are the only ones where profound energy transition policies are implemented; while the rest of the sectors follow current trends. The EV High and E-bike scenarios show that reducing the use of liquid fuels in transportation avoids energy shortages in the economy as a whole.

Table 5 shows the cumulated primary extraction ratio of aluminum, copper, lithium and manganese from mines versus the current estimated reserves and resources by 2050 [126,130–133]. The EV High scenario require higher amounts of copper, lithium and manganese than current reserves. For the cases of copper and manganese the depletion is mainly due to the demand from the rest of the economy. However, most of the lithium demand is for EV batteries, in the EV High scenario the demand of lithium for EV batteries alone depletes its estimated global reserves. The reserves of copper and manganese are also depleted in the Expected EV trends and E-Bike scenarios in 2050, but the depletion is mainly due

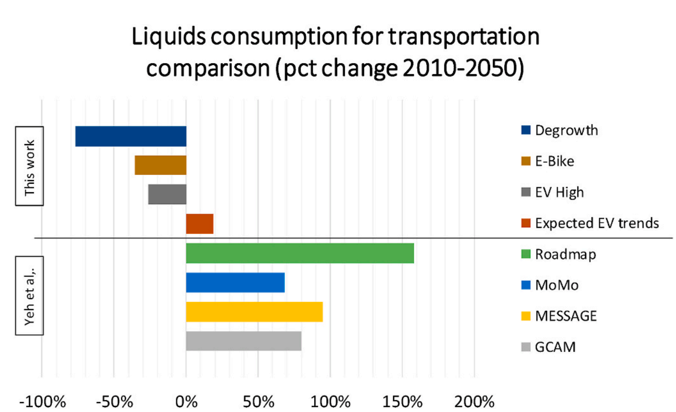

Fig. 7. Comparison of the results of different scenarios in the MEDEAS-W model with results in other models from Yeh et al., [27]. Own elaboration based on Fig. 3 of [27] and own estimates.

to the demand from the rest of the economy. Aluminum reserves are not depleted in any of the scenarios. The materials demand in Degrowth scenario does not deplete the reserves of aluminum, copper, lithium and manganese, due to the reduction in other uses driven by the reduction and subsequently stabilization of economic demand. However, for copper and manganese, the cumulated primary extraction approaches the level of current reserves (more 80%).

Hence, only the Degrowth scenario meets the decarbonization objective and avoids energy restrictions without exceeding the mineral reserves of critical materials related with lithium-ion batteries. Fig. 6a shows the transition in the number of vehicles by type in Degrowth scenario vehicles, which has to change very rapidly and radically to meet the decarbonization objective. The total number of vehicles would peak at around 2025, followed by a reduction in the number of vehicles by around 30% of the 2020 numbers. In this scenario, most vehicles in 2050 would be electric two-wheelers and e-bikes. LV would be almost entirely electric. The number of buses would remain roughly constant, the number of HV would be halved and trains will increase by 50% (the number of locomotives is around 500,000, not visible in the graph).

Fig. 6b shows the final energy consumption by type of vehicle over time in the Degrowth scenario. The evolution is similar to the number of vehicles; the energy consumption would also peak before 2025, but the energy consumption with relation to the maximum decreases much more, by 80% vs 30% for the number of vehicles. However, the weight of each type of vehicle is very different than in the previous graph: by 2050, the weight of the 2 wheelers in the energy consumption is very low and the liquid-fueled HV, that in this scenario have been partially shifted to electric trains instead of been replaced by hybrid heavy trucks, have the largest contribution to the total energy consumption. The energy consumption of electric trains in this scenario is also relevant (more than 20% of total energy consumption by 2050).

7. Discussion

The scenarios simulated in this paper of transport decarbonization show some clear trends that question the goals and strategies commonly recommended by international and national institutions and more extensively explored by the modeling community, which overwhelmingly focuses solely on technological solutions of efficiency improvements and vehicle replacement without questioning the current cultural patterns of mobility. Hence, the potential for behavioural and system change is usually disregarded [42,50,51]. Our results show that, the aim of reducing −80% GHG in transportation by 2050 from current levels can only be achieved under very strong policies. Such policies involve a radical shift towards light electric vehicles, shift of road freight to electric train, ambitious recycling mineral levels, drastic reductions in the demand for transportation (especially for those more polluting such as aviation) and a significant decrease in overall economic activity. These changes would require a broader social and economic framework in the line of Degrowth [148–150], where current growth-oriented economies evolve towards a new system that fulfills human needs without the necessity for continuous growth.

The projected liquids consumption for transportation obtained in this work is compared, in Fig. 7, with the corresponding liquids consumption projected by Yeh et al. [27], showing the results of BAU scenarios implemented in GCAM, MESSAGE-Transport, MoMo and Roadmap models. In all of the scenarios reported in Yeh et al., liquids consumption for transportation is expected to increase substantially over the coming decades, more than 50% the level of 2010 for all the models analyzed. This implies an expansion of global emissions far beyond any decarbonization objective. The models analyzed by Yeh et al., estimate emissions in 2050 of between 11 and 18 $GtCO_2$, well above those obtained in the alternative scenarios of this work. On the other hand, in the Expected EV Trends scenario, which is the one whose hypotheses are most similar to these scenarios, the increase in liquid fuel consumption increases only slightly, since physical limits to oil

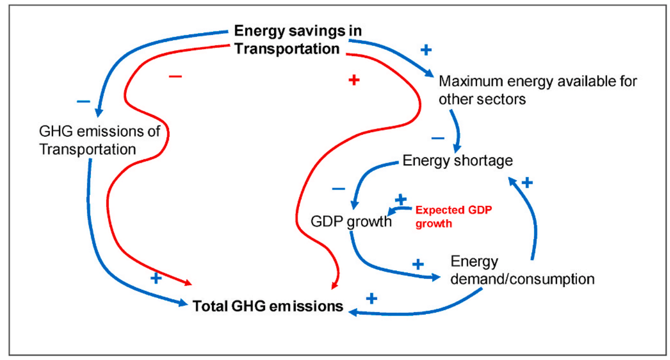

Fig. 8. Main feedback loops of the MEDEAS-W model with relation to energy savings in the transportation sector.

extraction appear in this scenario resulting in energy-economy feedbacks that ultimately restrict economic growth.

The Degrowth scenario, by drastically reducing total transportation demand combined with vehicle shifts which mimic behavioural changes within a degrowth paradigm, manages to significantly reduce liquids consumption in transport, but these hypotheses are far from what other models consider (see Table A. 1 and Appendix 1).

Mineral depletion is a problem, especially if recycling rates remain very low. If for example the mineral recycling rates would remain constant at current levels in the Degrowth scenario, the reserves of copper and manganese would be then also depleted by 2050. However, even in scenarios with a very high increase in recycling rates, the deployment of electric vehicles still finds limits. For example, in the EV High scenario, in which the recycling rates of copper, lithium and manganese increase to 57%, 30% and 74% from current ~28.5%, ~15% and <~37%, respectively, all the current estimated reserves would have already been extracted by 2050. This result corroborates what has been shown in recent studies, for example Valero et al. [36] estimates that the expected bottleneck time for lithium will be in 2042–2045 and manganese in 2038–2050. Other works [124,152] also conclude that there could be imbalances in supply and demand for different minerals required for the infrastructure for the energy transition. Further work could be directed to model different EV batteries sub-technologies in order to allow for substitution effects of potentially scarce minerals. It is also noteworthy that in this study only the material requirements associated to the EV batteries have been considered, representing thus a lower bound. Future work could expand the assessment by including the material requirements associated to internal wiring and EV motor, the EV chargers [153], the grid to connect and charge the EV batteries [154], the catenaries to electrify the railways which today still function mainly with diesel-powered engines (just ~27% of the world railway lines are currently electrified [155]), etc.

Moreover, given that we are using the Recycled Content (RC) definition for recycling rates, we are a priori assuming the availability of sufficient waste mineral to be reintroduced into the system, which may not always be the case, especially for those minerals for which the strongest increase in demand is expected over the next few decades. On the other hand, it is also worth highlighting the fact that improving the recycling rates of metals can be very difficult. This is due to several factors, such as inappropriate design, special properties which need complex recovery processes when mixed, thermodynamic limits, a high mobility of products due to international trade, a generally low awareness of a loss of resources or the lack of an appropriate infrastructure for the end-of-life management of complex products etc. [36]. Additionally, lithium mining involves huge environmental impacts [156].

Furthermore, the model shows the effects of the energy-economy feedback and the rebound effect[2] produced by saving energy in a specific sector. The influence diagram of Fig. 8 illustrates this effect. The results of applying energy saving policies to transportation are the following. On the one hand, due to decarbonization policies in transportation, the consumption of liquid fuels is reduced and total GHG emissions go down in this sector. On the other hand, more liquid fuels are hence left for other economic sectors; while the shortage of liquid fuels is delayed for some years and the economy grows more than it would do in the absence of saving policies. The final result is that in total, GHG emissions does not decrease as intended by the transport decarbonization policies, and even they could increase in absolute terms (i.e.,"backfire") in the absence of energy scarcity and having instead assumed heterogeneous distribution of income in the rest of sectors after the savings in the transportation sector. Since GDP tends to grow because the current economic system is based on this objective, a constant increase in energy demand is almost impossible to avoid as long as the economic growth continues and only energy scarcity makes emissions go down. This supports the difficulties that many have observed to decoupling economic, energy and GHG growth [158,159].

8. Conclusions

This article studies four decarbonization strategies for global transportation by 2050, using the MEDEAS-W model that combines different options of electrification, substitution of vehicles, modal shifts and demand-side management. We compare scenarios considering different technological substitution measures with a scenario including drastic changes in the mobility patterns [42,45,46,52], and which can be representative of an interpretation of global Degrowth transportation scenario, which to the best of our knowledge has not been tested to date in a quantitative framework [44]. It is noteworthy that conventional studies in the literature only find that the decarbonization of global transportation is possible under the unreliable assumption that in the future currently uncertain technologies such as advanced biofuels, hydrogen, fuel cells or CCS are massively available commercially and at a sustainable level.

The scenarios simulated in this paper show some clear trends that question the common strategies presented as decarbonization targets by some international and national institutions. The current trends of electric vehicle growth fall far short of reducing GHG emissions and, in addition, end up causing undesired economic contraction due to a lack of liquid fuels caused by peak oil. The scenarios based on a rapid replacement of conventional ICE vehicles by electric ones avoid the shortage of liquid fuels for some years and enable economic growth to continue, but in the mid-term, the scarcity of liquid fuels appears and these scenarios cannot reduce GHG emissions to strongly decarbonize the global transportation system by 2050.

The massive use of electric vehicles encounters significant problems for some key mineral reserves, such as lithium, copper and magnesium. This makes the high electrification of light vehicles unfeasible without severe recycling policies. The recycling of strategic minerals for batteries should therefore be set as a priority objective before incentivizing the mass-production production of these vehicles.

The substitution of the present cars by very light vehicles, such as e-bikes and mopeds, would help to delay the liquid fuels shortage in the short term and, therefore, the economic decline. This scenario requires less minerals and electricity as well; however, since it also stimulates economic growth, the final reduction in emissions ends up being modest.

Freight transportation with heavy vehicles, as well as air and water transport are the most difficult modes to electrify and therefore to reduce their GHG emissions. The scenarios simulated in this paper are aligned with the literature [41,97] and show that a radical transition in global freight is required for the decarbonization of global transportation. Scenarios that consider modal shift from ICE heavy trucks to electric rail allow for a significant reduction in emissions from freight transport.

Of the explored scenarios, only the one with very strong policies of a radical shift towards light vehicles, ambitious mineral recycling, plus a drastic reduction in the demand for transportation, especially for air transport, achieves the combined objectives of energy savings and GHG emissions reductions. This scenario mimics the behavioural change that the Degrowth paradigm proposes towards sufficiency and equality instead of efficiency. Hence, we find that the implementation of policies to improve behavioural change and transport mode shifting towards a low carbon transport mode would be necessary to meet ambitious decarbonization targets in line with the 1.5–2 °C target. These assumptions are however generally outside the political and economic options of the moment. In fact, the history of failures in the attempts to reduce GHG emissions suggests that the only way to achieve decarbonization is a profound change in the dominant economic paradigm. Future work will be directed to a more comprehensive modeling of the Degrowth scenario given that in this work profound changes have been explored only for the global transportation and electricity sectors.

The promotion of public transport and traffic restrictions have been used in several cities and show a great potential for energy saving and GHG emissions reductions [8]. Moreover, the disaggregation by region and income household's levels would be particularly important to model the transition, particularly in some travel modes such as air transport characterized by high income inequalities. These policies and others, such as shared mobility and the impact of taxes on different fuels, will be contemplated in newer versions of the model.

CRediT authorship contribution statement

Ignacio de Blas: Methodology, Software, Writing - original draft, Visualization. **Margarita Mediavilla:** Conceptualization, Software, Supervision. **Iñigo Capellán-Pérez:** Methodology, Software, Validation, Writing - review & editing. **Carmen Duce:** Resources, Writing - review & editing.

Declaration of competing interest

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

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[2] Not to be confounded with the "rebound effect" which is the result of the economic responses when there is a reduction of the cost of provision of certain energy services, due to an improvement of energy productivity of providing energy services [157].

valuable inputs and comments on early versions of the manuscript.

Appendix 1. Overview of relevant works focusing on transport decarbonization

Table A 1
Overview of relevant works focusing on transport decarbonization including (1) mainly technological changes, (2) mainly lifestyle changes of citizens and (3) combining citizens' lifestyle and technological changes. We follow here the definition of citizens' lifestyle changes proposed by Van den Berg et al. [42] based on the ASI framework (*avoid, shift, improve*), in which only "*avoid*" and "*shift*" are considered lifestyle changes while "*improve*" features such as efficiency improvements and technological substitutions when providing the same output but using a different set of inputs are not.

References	Measures analyzed	Regional scope	Methodology	Reduction of GHG emissions projected/main conclusions
(1) GHG mitigation in transportation applying mainly technological change options				
Van der Zwaan et al., 2013 [29]	Focus on light-duty vehicles: application of a carbon tax to drive technological shifts between 12 car technology types including ICE, liquid biofuels, hydrogen fuel, EV and hybrids. CCS technologies are considered in the upstream, electricity and hydrogen sectors.	Europe	Simulation forecast with the global bottom-up energy systems model TIAM-ECN	For a global 4 W/m2 forcing constraint, +40% GHG emissions in 2050 and -50% in 2100 wrt to 2010 are found for Europe. The use of hydrogen in internal combustion engines and fuel cells gradually becomes the dominant transport technology.
Carrara and Longden, 2017 [28]	Focus on the freight transportation sector. Application of a carbon tax to drive technological shifts gradually phasing out traditional ICE vehicles, substituted by hybrid, plug-in hybrid and electric drive vehicles and with the substitution of oil with biofuels.	World grouped into 13 regions	Simulation forecast with the IAM WITCH	No road freight emission reductions by 2050. By 2100: total emissions reduction of nearly 100% in the 450 scenario with road freight dominated by electric drive vehicles. The decarbonization of the freight sector tends to occur in the second part of the century and that the sector decarbonises by a lower extent than the rest of the economy. Decarbonising road freight on a global scale remains a challenge even when notable progress in biofuels and electric vehicles has been accounted for.
McCollum et al., 2017 [43]	Focus on light-duty vehicles choice: representation of heterogeneous consumer groups with varying preferences for vehicle novelty, range, refuelling/recharging availability, and variety.	World	Simulation forecast in MESSAGE-Transport IAM	Consumer preferences tend to slow down the transition to alternative fuel (low-carbon) vehicles. Hence, stronger incentives (price and/or non-price based) would be needed to transform the global fleet of passenger vehicles, at least in the initial market phases of novel alternatives.
Karkatsoulis et al., 2017 [32]	Objective: assess the macroeconomic and sectorial impacts of the transformation of transport patterns, and the diffusion of new technologies and fuels following the policy and technology assumptions presented in the White Paper on Transport of the European Commission. The decarbonization scenarios draw on the policy and technology assumptions presented in the White Paper on Transport of the European Commission. The policy package includes CO2 emissions standards for light duty vehicles with strongly decreasing values in the future, development of recharging infrastructure, promotion of advanced biofuels and a series of additional measures, such as improvement of energy efficiency of heavy duty vehicles, ships and aircraft, pushed by standards; wide deployment of intelligent transport systems; changes in vehicle and company car taxation; and internalisation of local externalities (for air pollution, noise and accidents.	European Union	Simulation forecast with the CGE GEME3-T (GEM-E3 linked with the PRIMES-TREMOVE energy and transport sectors model)	Target EU: 60% emission reduction in transport in 2050 wrt to 1990. Model projection: decrease about 0.1–0.25% of GDP in 2040, rapid recovering in 2050. Major uncertainties with relation to the costs of electric cars and advanced biofuels. In the baseline scenario final energy demand in transport decouples from transport activity growth in the long run, due to efficiency gains of transport means Transport restructuring affects the economy through multiple channels: investment in infrastructure, purchasing and manufacturing of new technology vehicles or the production of alternative fuels, such as biofuels and electricity.
Yeh et al., 2017 [27]	Models include a diversity of options: transition to more efficient and low carbon fuels' vehicles, load factor changes, mode shifts and travel reductions.	World	Comparison of 4 simulation forecast models: iTEM (International Transportation Energy Modeling) compares: GCAM (PNNL), MESSAGE-Transport (IIASA), Mobility Model MoMo (IEA) and Roadmap (ICCT)	Comparison of results at 2050 applying a scenario consistent with a 2 °C/450 ppm target by 2100. Only MoMo achieves significant reductions in the Transportation sector by 2050 (~40% wrt to current levels). IAMs only reduce wrt to baseline trends. Technological shifts dominate over behavioural ones. IAMs favour the use of low

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Table A 1 (*continued*)

References	Measures analyzed	Regional scope	Methodology	Reduction of GHG emissions projected/main conclusions
(1) GHG mitigation in transportation applying mainly technological change options				
				carbon fuels followed by efficiency improvements, whereas transport-only and expert-based models favour mainly efficiency improvements of vehicles followed by mode shifts and low carbon fuels. Load factor and overall demand reductions are negligible in all models.
McCollum et al., 2018 [3]	Focus on light-duty vehicles choice: Develop and implement representations of consumer preferences (financial and non-financial) in 6 global energy-economy models (based on van Sluisveld et al. [51], formulation). A diversity of Alternative Fuel Vehicles (AFVs) considered: ICEs running on biofuels or natural gas, battery-electric vehicles, plug-in hybrid-electric vehicles and hydrogen fuel cell vehicles powered by low-carbon electricity and hydrogen.	World	Simulation forecast in 6 energy-economy models: GEM-E3T-ICCS, IMACLIM-R, IMAGE, MESSAGE-Transport, TIAM-UCL, WITCH	2050: the average cumulative emissions reduction estimated by the models for the OECD is 17 GtCO2 (range 9–24 GtCO2) in the 'AFV Push (+100 US$ per tCO2)' scenario, but only 8 GtCO2 (range 1–22 GtCO2) in developing Asia. Diverse set of measures targeting vehicle buyers is necessary to drive widespread adoption of AFVs. Carbon pricing alone is insufficient to bring low-carbon vehicles to the mass market, though it may have a supporting role in ensuring a decarbonized energy supply
(2) GHG mitigation in transportation focusing on citizens' lifestyle change options				
Dietz et al., 2009 [47]	Analysis of 33 specific actions achievable by households combined in 17 action types. For each action, the current penetration + potential future penetration based on behavioural plasticities. For mobility: fuel-efficient vehicle, routine auto maintenance, driving behaviour, carpooling and trip-chaining.	USA	Literature review + static analysis	8% carbon emission reductions from baseline.
Girod et al., 2013 [49]	Modal shift in 7 categories: walking, bicycle, bus, train, car, high-speed train and airplane. It explicitly applies a TTB (share of income) and TTB (time per day spent on transportation) as travel constraint	11 world regions	Simulation forecast with the TRAVEL model (submodule of the IMAGE/TIMER IAM).	Reduction of CO2 emissions by ~50% by 2100 compared to the baseline trends combining different behavioural options (still this would be +50% GHG emissions by 2100 than current levels). Combining behavioural changes and a carbon tax (of 200 USD/tCO2) results in emission reductions close to the reduction required in the transport sector for the 2 °C climate target.
Cosme et al., 2017 [44]	Literature review of academic degrowth policy proposals	World	Literature review of 128 peer-reviewed articles	The majority of degrowth proposals are national top-down approaches, focusing on government as a major driver of change, rather than local bottom-up approaches, as advocated by many degrowth proponents. The most emphasised aspects in the degrowth literature are related to social equity, closely followed by environmental sustainability. There is a need for a deeper analysis of how degrowth proposals would act in combination. Mobility: Redirect investments away from infrastructure in fast and car-based models of transport to slow-mode ones
Wynes and Nicholas, 2017 [46]	Comparison of high-impact and low-impact individual actions	OECD countries	Review of 148 scenarios	High-impact actions, such living car-free, avoiding airplane travel
Wynes et al., 2018 [45]	Review of studies analyzing the impact of different types of policy interventions (rewards, prompt, justification, feedback, commitment and cognitive dissonance)	3 USA states and 2 EU countries	Literature review of 5 empirical studies	571 [54–1041] kgCO_2e/year/driver (i.e., 3.2% [0.3–5.8%] of the average USA's emissions reported in 2014)
Lacroix, 2018 [48]	Literature review to gather baseline data for the average carbon footprint by sector as well as comparative data for the carbon footprint of behaviors. Finally, calculate the range of achievable GHG emissions reductions for each behaviour expressed as a portion of the average individual's total GHG emissions.	High-income countries	Literature review + static analysis	Without accounting for air transportation frequency reduction, just <10% GHG emissions reductions.

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Table A 1 (*continued*)

References	Measures analyzed	Regional scope	Methodology	Reduction of GHG emissions projected/main conclusions
(1) GHG mitigation in transportation applying mainly technological change options				
	For mobility: switching to a fuel-efficient car, eco-driving and teleworking, air transportation frequency.			
van Sluisveld et al., 2016 [51]	Implementation of lifestyle measures for residential energy use, mobility and waste management. In mobility: reduced vehicle use and modal shift to public transport (TMB and TTB). Comparison of results with/without lifestyle changes in 2 scenarios: baseline (BAU) + mitigation scenario <2 °C (through carbon price constraint).	World	Simulation forecast with the IAM IMAGE	GHG reduction in transport sector of ~35% by 2050 compared to baseline emissions and reduction of 7–18% in mitigation scenarios (overlapping of carbon tax and behavioural change policies). Negligible indirect implications in the industry and energy supply sectors.
van de Ven et al., 2018 [50]	Implementation in the GCAM model of a suite of behavioural policies which do not require any personal up-front investment affecting different sectors (food, housing, mobility). For mobility, the following options are considered: transport commuting, carpool commuting, teleworking, urban cycling, car sharing, avoid short flights and closer holidays. Three different profiles (enthusiastic, conscious and convenient) for the adoption of green behaviour are defined. By-default technological improvement changes included in the simulations.	European Union	Simulation forecast with the IAM GCAM	Mainly domestic CO2 savings. Total cumulated GHG emissions reduction from 2011 to 2050 wrt to baseline emissions: 4.2% (enthusiastic), 3.1% (conscious) and 2% (convenient).
van den Berg et al., 2019 [42]	Avoid, shift and improve (ASI) framework, in which only *avoid* and *shift* are considered lifestyle changes while *improve* features such as efficiency improvements and technological substitutions when providing the same output but using a different set of inputs are not.	World	Literature review of the implementation of lifestyle changes in IAMs	Most modeling effort directed to *improve* and to a lesser extent, on *shift*. Still, the transport domain has been modeled relatively often with regards to lifestyle changes. Recommendations for better representing lifestyle change in IAMs: ASI framework, intent and impact perspectives, trade-offs between exogenous inputs and endogenous modeling.
(3) GHG mitigation in transportation combining citizens' lifestyle and technological change options				
IEA/OECD, 2009 [54]	Implementation of the BLUE Map scenario which includes changes in behavioural changes on top of technological changes. The Baseline increase in LDV travel is shifted to rail, bus and non-motorized modes. Of the Baseline increase in air travel, most is shifted to high-speed rail and coach. A share of the Baseline increase in both LDV and air travel is assumed to be avoided, being displaced by increased use of teleworking and greater use of videoconferencing in lieu of air travel.	World	Simulation forecast with the IEA ETP Mobility Model (MoMo).	Worldwide LDV travel in 2050 might be cut by 25% compared to the Baseline scenario, resulting in a 50% (instead of 80%) increase over 2005 levels. Air travel is also cut by 25% in 2050 compared to the Baseline, resulting in a tripling rather than a four-fold increase over 2005 levels.
Moriarty and Honnery, 2013 [52]	Focus on passenger transport. Technical solutions: energy efficiency improvements, alternative fuels and power systems. Non-technical solutions for greener transport: urban land use changes (e.g., residential density increases), policies focusing to slow down car travel speeds and car access (e.g., lower speed limits and parking restrictions)	World	Literature review	It is most unlikely that technical solutions alone can deliver anywhere near the GHG emission reductions needed.
Sims et al., 2014 [5]	Proposal of a set of transport technologies and practices with potential for both short- and long-term de-carbonization and the transition to a 100% renewable transport system: (i) Modal shift with public transport, cycling and walking displacing private motor vehicle use; (ii) Urban planning by reducing distances within urban areas; (iii) Urban planning to reduce private motor vehicle use through parking and traffic restraint; (iv) Modal shift by reducing aircraft and Light Duty Vehicles (LDV) travel through high-speed rail alternatives; (v) Modal shift of freight by displacing High Duty Vehicles (HDV) towards railways.	World	Literature review	A reduction in total CO2eq emissions of 15–40% could be plausible compared to baseline activity growth in 2050
Grubler et al., 2018 [53]	Scenario narrative of "Low energy demand" (LED): quality of life, clean local	World	Simulation forecast with the IAM framework MESSAGEix-GLOBIOM	Mobility: % change in energy demand (2020–50):

(continued on next page)

Table A 1 (*continued*)

References	Measures analyzed	Regional scope	Methodology	Reduction of GHG emissions projected/main conclusions
(1) GHG mitigation in transportation applying mainly technological change options				
	environments and widely accessible technologies. Bottom-up quantifications of changes in activity levels, energy intensities and final energy demand to 2050 for all the major energy end-use services and corresponding upstream sectors. Substantial efficiency improvements + technological improvements (extensive management through ICTs and mobile devices) + behavioural changes (sharing of devices&vehicles, end-user roles, telework, etc.) lead to absolute dematerialization of (increasing) activity levels and energy supply. In mobility: shift from private to shared (electric) vehicles and public transport (including autonomous vehicles), telework, assumptions on urban planning changes, increase of load factors, electrified rail for long-distance inter-urban mobility.			End-use mobility services: ~ −60%. Upstream freight transport: −28% (North) and −12% (South). Global final energy demand by 2050 reduces to 245 EJ, around 40% lower than today (global-average final energy demand ~27 GJ/year/person). Electrification of the economy. Rebound effect not considered.
van Vuuren et al., 2018 [56]	A set of uncommon assumptions in IAMs is tested towards faster and more radical decarbonization without the need of CDR, including lifestyle change, including additional reduction of non-CO2 GHG and more rapid electrification of energy demand based on renewable energy. The lifestyle change scenario (LiStCh) assumes a radical value shift towards more environmentally friendly behaviour, including a healthy, low-meat diet, changes in transport habits towards less CO2-intensive transport modes and a reduction of heating and cooling levels at homes.	World	Simulation forecast with the IAM IMAGE	The volume of CDR or BECCS can be limited by a range of societal and technological factors and choices.
García-Olivares et al., 2018 [31]	Discussion of the main proven and expected technologies, efficiency improvements, new infrastructure and policy measures for the sustainability of each transportation sector (including minerals availability). Priority to direct electricity use (e.g., with catenary-based systems) over batteries and fuel-cells-respectively: electrification of land transport (light electric vehicles and public electric transport for urban mobility, metropolitan and regional transport), fuel cells (natural gas produced from (captured or renewable) CO_2 and hydrogen, instead of using hydrogen due to its worse stability) for marine transport and air transport and demand reduction through behavioural changes. Behavioural changes are not explicitly considered, but rather assumed to deal with the necessary demand reduction in a context of increased total population and similar activity levels than in world transport in 2014 (excepting aircraft fleet which would fall to 1/2).	World	Literature review + static analysis: proposal of a 100% renewable-based global transportation system taking as reference current data and expected efficiency and technological improvements	A 0% GHG emissions transport system that delivers similar total activity levels than world transport in 2014 would demand about 18% less energy (100% renewable). The shipping and air sectors would notably increase their consumptions: 163% and 149%, respectively, due to the need to produce natural gas from electricity.
van Sluisveld et al., 2020 [55]	Consideration of insights from socio-technical transition (MLP) in IAM to develop new quantitative scenarios. 3 alternative scenarios tested: (Default) techno-economic optimisation -rational economic agent-, (TechSub) pro-technological substitution driven by incumbents and (RegChange) demand reduction through behavioural changes driven by new actors (assuming no CCS neither nuclear availability). Efficiency and technological improvements embedded in the framework. Full-system mitigation goal (through carbon price constraint): −80% GHG EU 2050 wrt 1990 levels.	European Union	Simulation forecast with the IAM IMAGE + Multi-Level Perspective (MLP) approach	%GHG reduction in transportation wrt to 2010: −65% (Default) −70% (TechSub) −80% (RegChange)

(*continued on next page*)

Table A 1 (*continued*)

References	Measures analyzed	Regional scope	Methodology	Reduction of GHG emissions projected/main conclusions
(1) GHG mitigation in transportation applying mainly technological change options				
This work	In the Degrowth scenario: combination of technological improvements (*improve*) with demand-side solutions as the replacement of conventional ICE vehicles by light electric vehicles and non-motorized modes (*shift*) as well as a drastic reduction in total transport demand, especially in the most polluting modes such as aviation (*avoid*).	World	Simulation forecast with the IAM MEDEAS-World	−80% GHG emissions reduction in 2060 wrt to 2020 (see section 4)

IAM: Integrated Assessment Model; ICE: Internal Combustion Engine; ACV: Alternative Fuel Vehicle; LDF: Light Duty Vehicle; CCS: Carbon Capture and Storage; MLP: Multi-Level Perspective; CDR: carbon dioxide removal; BECCS: Bioenergy with CCS.

Appendix 2. BAU scenario inputs in MEDEAS-W

Table B 1
Overview of the most relevant assumptions and inputs for the BAU scenario. See also Table 4.

Population growth: SSP2 (stabilization at 10,000 million people by 2100
GDPpc planned: Scenario-dependent (see section 5)
Target labor share (2050) 52%
A matrix: constant (2009)
Efficiency improvements (Final energy intensity): trends by sector/households and fuel, Own estimation
Global afforestation program? No
Nuclear installed capacity: constant at current levels
Recycling rates of minerals (19 minerals) Current recycling rates (RC) scenario-dependent (see section 5)
Annual capacity growth of RES for electricity/Potential
Hydroelectric 3.8%/1 TW
Geothermal 4.2%/0.3 TW
Bioenergy shared potential for heat, liquids and electricity 7.8%
Oceanic 20%/0.05 TW
Wind onshore 20%/1 TW
Wind offshore 20%/0.25 TW
Solar PV 200 MHa shared on land + PV rooftop 20%/100 MHa
Solar CSP depending on available urban land
Pumped Hydro Storage 15%/0.25 TW
Target capacity of RES for heat (2050)(commercial & non-commercial) 4,4 TW
Bioenergy
Marginal lands: 386 MHa [160]
2nd Gen cropland +11%/yr
3rd Gen cropland (starting 2025) 11%/yr
Residues (starting 2025) 20%/yr 11 EJ/yr
Non-renewable energies depletion curves
Oil [140]
Gas [140]
Coal Best Guess [12]
Uranium [161]
Switches
Climate Change impacts: not activated
EROI feedback: activated
Energy limits feedback: activated
Inter-final energy replacements: activated

Appendix 3. Historical trends of household vehicles

Figure C. 1 presents the historical percentages of the stock of electric, hybrid and gas powered vehicles relative to the number of vehicles of each type (four-wheelers, two-wheelers, heavy). The historical data of the number of vehicles are taken from the IEA and the OICA [102,141,142,146]. The fitted extrapolation trends are also represented.

For electric four-wheelers (BEV + PHEV), two different extrapolations are shown in figure (a): the polynomial that best fits historical data and the lineal based on the forecasts to 2030 from manufacturing automotive companies from the IEA [143,144]. The historical stock of BEV + PHEV is very small and this makes extrapolation complex. Its number has also been increasing rapidly over the last few years, driven by government incentives, which makes the extrapolation of trends even more difficult. This is why both extrapolations are done.

For the rest of the vehicles of Figure C. 1, the best fit extrapolation is taken. The growth of electric two-wheelers (d) is so fast that the extrapolation of its percentage reaches 100% long before 2050. This fast growth of two-wheelers is due to the ban in China on conventional two-wheelers, though this policy is not expected to be applied in the short term to the rest of the world. Nevertheless, since the electrical substitution of two-wheelers is an easy one in terms of technical difficulties and price, we assume that they reach 100% substitution by 2050, following the trends scenario.

For hybrid and gas heavy vehicles (e, f), the data are very scarce and subject to great uncertainty, though the percentages are very small and are not expected to grow abruptly in the mid-term.

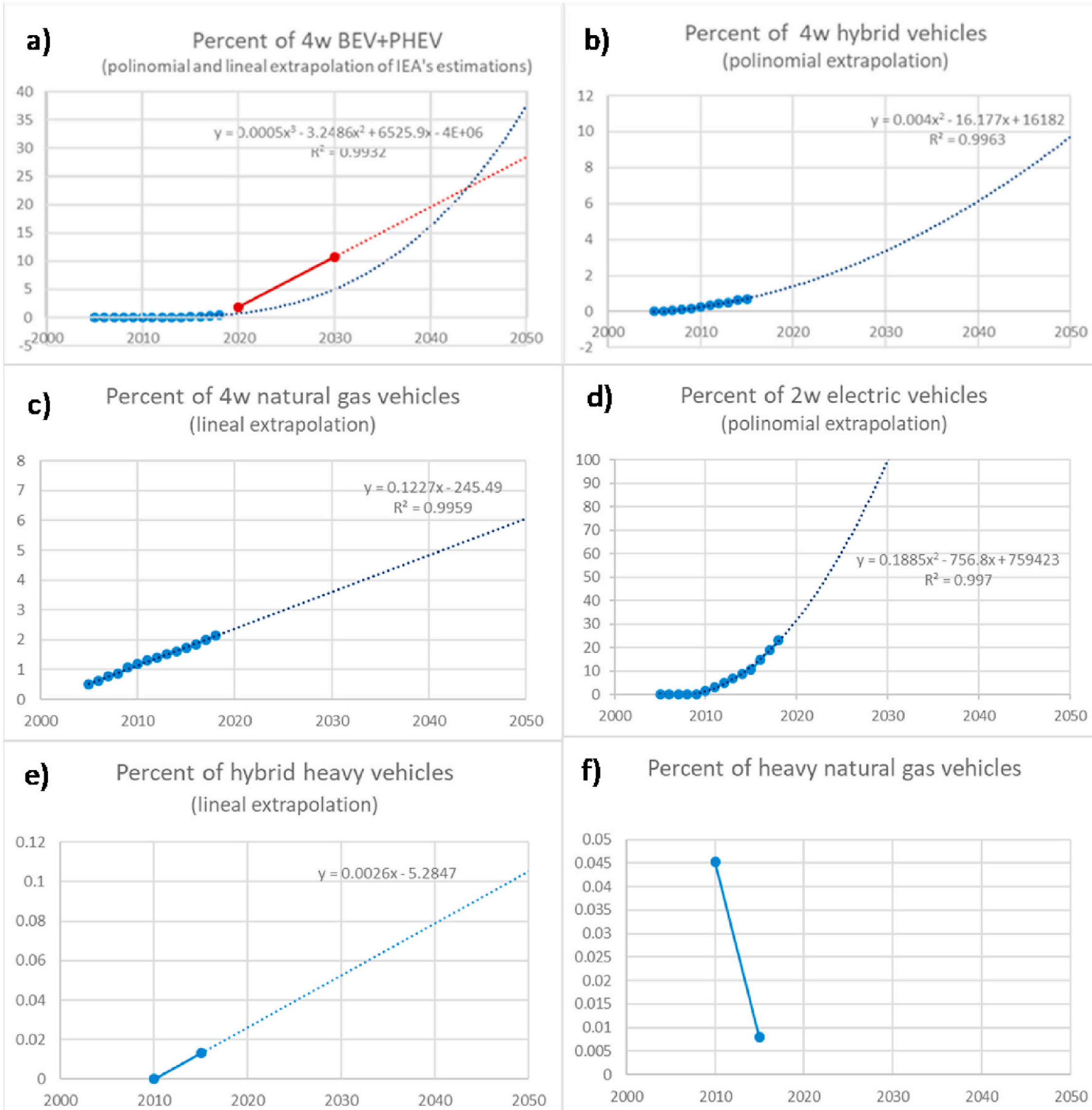

Fig. C 1. Historical percentage of vehicles by type and their extrapolation.

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