Energy 239 (2022) 122197

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Regional energy diversity and sovereignty in different 2 °C and 1.5 °C pathways

A.F. Hof [a, b, *], K. Esmeijer [c], H.S. de Boer [a, b], V. Daioglou [a, b], J.C. Doelman [a], M.G.J. den Elzen [a, d], D.E.H.J. Gernaat [a, b], D.P. van Vuuren [a, b]

[a] PBL Netherlands Environmental Assessment Agency, The Hague, Netherlands
[b] Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, Netherlands
[c] Ministry of Economic Affairs and Climate, The Hague, Netherlands
[d] Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, the Netherlands

ARTICLE INFO

Article history:
Received 30 April 2020
Received in revised form
24 September 2021
Accepted 25 September 2021
Available online 28 September 2021

Keywords:
Energy security
Energy trade
Scenarios
Climate
Integrated assessment
Energy diversity

ABSTRACT

Achieving the objectives of the Paris Climate Agreement requires a fast transition of the energy system. This leads to consequences for energy security, which a central element of the energy strategy of many countries. Important dimensions of energy security are energy diversity and energy sovereignty. The main objective of this study is to assess how different strategies and climate objectives affect these dimensions. For this, we developed a set of model-based mitigation scenarios that limit global warming to below 2 °C and 1.5 °C for 16 world regions. The scenarios differ in the energy transition strategy, focusing either more on intermittent renewables or lifestyle change. We show that energy supply diversity increases in deep mitigation scenarios in practically all regions, especially in India and China. This is due to strong growth of bioenergy and intermittent renewables, together with less fossil fuel use. There is also a substantial decrease in total energy trade in mitigation scenarios with a strong focus on intermittent renewables. Without such a strong focus on renewables, the decrease in oil and coal trade is offset by additional trade in bioenergy. However, more trade in bioenergy leads to a higher diversity in energy exporters.

1. Introduction

Greenhouse gas (GHG) emissions need to be reduced strongly to meet the Paris Agreement's climate objectives of limiting global average temperature increase to well below 2 °C and pursuing efforts limiting it to 1.5 °C [1–3]. This will require energy systems that differ much from today. This will also automatically impact energy security [4,5]. As energy security forms a central element of the energy strategy of many countries, including the EU [6] and the USA [7], an important question is how different strategies to achieve the Paris Agreement objectives affect energy security.

Although the concept of energy security is widely used, there is no consensus on its precise interpretation, partly because it is strongly context-dependent [8]. A very general definition of energy security is “low vulnerability of vital energy systems”. APERC [9] identified the following three fundamental elements relevant for energy security: i) physical energy security, relating to *availability* and *accessibility* of energy resources, ii) economic energy security, relating to *affordability* of resource acquisition and energy infrastructure development, and iii) environmental sustainability, relating to the *acceptability* of energy resource use. To more formally analyse energy security implications of different energy transition strategies, Kruyt et al. [5] provided an overview of relevant indicators for these four dimensions of energy security. Indicators for availability focus on physical aspects such as reserve estimates and reserve/production ratios, indicators for accessibility focus on energy sovereignty (i.e. the degree to which countries have domestic control over energy systems; Jewell et al. [4], measured by aspects such as trade and diversity of fuels and suppliers, indicators for affordability focus on energy prices, and indicators for acceptability focus on non-carbon shares in total energy supply.

Energy transition scenarios can analyse the long-term energy security implications of different strategies to achieve the Paris climate objectives. Existing scenario studies on energy security

* Corresponding author. PBL Netherlands Environmental Assessment Agency, P.O. box 30314, 2500 GH, The Hague, Netherlands.
E-mail address: Andries.hof@pbl.nl (A.F. Hof).

https://doi.org/10.1016/j.energy.2021.122197

include Kruyt et al. [5]; Jewell et al. [4] and Cherp et al. [10]. Using the integrated assessment model IMAGE, Kruyt et al. [5] assessed a wide set of energy security indicators covering all four dimensions mentioned above of energy security for one baseline scenario and one 2 °C scenario, focusing on Western Europe. Jewell et al. [4] used the integrated assessment model MESSAGE to evaluate energy accessibility of 42 scenarios that limit mean global temperature increase to 2 °C. These scenarios were differentiated across three dimensions: level of energy demand, availability of mitigation technologies, and configuration of transport systems. Cherp et al. [10] applied two different integrated assessment models (REMIND and WITCH) to assess accessibility under different assumptions on GDP growth and fossil fuel availability. In the latter two studies, accessibility was further categorised into the elements of sovereignty (assessed by energy trade indicators) and resilience (assessed by the diversity of supply indicators).

Given the widely diverging strategies to achieve the Paris climate objectives, assessing the energy security impacts of these diverging strategies is crucial for a more balanced comparison of the advantages and disadvantages of such strategies. Crucial differences exist concerning the emphasis on intermittent renewables, changes in lifestyles, and the use of negative emissions obtained by carbon dioxide removal (CDR) measures. Regarding the latter, optimal mitigation strategies generally lead to extensive use of CDR measures. These allow offsetting of emissions from sectors where CO_2 reductions are hard to achieve due to technical, economic or political constraints. By far, the most important CDR measures in existing mitigation scenarios are afforestation and bioenergy with carbon capture and storage (BECCS) [11]. However, there are only very few operating BECCS projects today [12], and there is a heavy debate about the potential and desirability of large-scale application of bioenergy and CCS. This debate focuses mainly on issues related to i) the impact of bioenergy on food production, water scarcity, and biodiversity, ii) concerns about biomass feedstock not being carbon neutral, iii) risks of carbon leakage from storage reservoirs [12–17], and iv) the risks associated with an initial overshoot of the carbon budget [18]. Reasons why biomass feedstocks may not be carbon neutral include i) converting land to biomass crops may lead to increases emissions, ii) emissions related to production, pre-treatment, and transport of biomass, ii) conversion processes, and iv) carbon debts (the time required to re-absorb the emissions emitted in the atmosphere) [12].

Because of these potential drawbacks of BECCS, alternative strategies that depend less on CDR measures have been developed, leading to different pathways [3,19–23]. Two often discussed strategies to limit the use of BECCS are based on a more prominent role of lifestyle change [20,22,23] and more optimistic expectations regarding integration of intermittent renewable energy and electrification by sector coupling [19,23–29]. Such pathways lead to widely different energy systems, with important implications for energy security.

This study's main objective is to assess how different strategies and climate objectives affect the accessibility aspect of energy security. We evaluate different 2 °C and 1.5 °C scenarios on energy diversity and sovereignty. Compared to earlier scenario studies on energy security, the main novelty of our study is that we take into account different climate targets (more specifically, the 1.5 °C target) and lifestyle change. The scenarios have been developed by the integrated assessment model IMAGE [30]. Apart from a scenario with considerable CDR, scenarios in which the use of CDR measures are limited by more extreme lifestyles change and more optimistic assumptions on the penetration of intermittent renewables. As energy security is primarily a national issue, we provide the results for ten individual countries and six world regions. Moreover, we consider all major traded fuels (oil, coal, natural gas, and bioenergy) separately, as they differ in their regional characteristics of demand and supply.

2. Methodology

We used the IMAGE 3.0 model to develop three scenarios for both the 2 °C and 1.5 °C targets. For each of the scenarios, we analysed the implications for energy security. Below, a short overview of the IMAGE model is provided, followed by a description of the scenarios and the method used for analysing energy accessibility. More detailed information on the IMAGE model can be found in Supplementary Info, in Stehfest et al. [30]; and on the dedicated website (https://models.pbl.nl/image) and on the scenarios in Van Vuuren et al. [23] and Esmeijer et al. [31].

2.1. IMAGE model

IMAGE 3.0 is a comprehensive ecological-environmental model framework that simulates the environmental consequences of human activities worldwide.

IMAGE represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change and biodiversity. The model is a simulation model, i.e. changes in model parameters are calculated based on information from the previous time step. The model includes a detailed description of the energy and land-use system and simulates most of the socio-economic parameters for 26 regions and most of the environmental parameters on the basis of a geographical grid of 30 × 30 min or 5 × 5 min (depending on the variable). Important inputs to the model are future developments of population, the economy, lifestyles, policies, and technology change.

The main components in the human system describe the demand for energy and food and their production that can cause land-use changes and emissions of carbon dioxide and other greenhouse gases. The energy system, which is the most relevant for our analysis, is modelled by TIMER (The IMage Energy Regional model; [32,33]). Fig. 1 depicts a flow diagram of TIMER.

The demand for energy services depends on future economic activity, which is driven by input parameters (model drivers) on socioeconomic developments (GDP per capita, population, value added by sector, private consumption, and lifestyle assumptions). Five economic sectors are considered: industry; transport; residential; public and private services; and other sectors (mainly agriculture). For each of these sectors, final energy use is driven by the demand for energy services and autonomous and price-induced energy efficiency improvements. The choice for secondary energy carrier is made based on its relative costs. Energy prices link the demand module with the energy supply and conversion model (described below), as they respond dynamically to changes in demand, supply and conversion. The prices of secondary energy carriers depend on direct production costs, energy and carbon taxes, and premium values. The last two reflect preferences, environmental policies, infrastructure (or the lack of infrastructure) and strategic considerations. The premium values are determined in a model calibration process in order to correctly simulate historical market shares on the basis of simulated price information.

A key factor in the energy supply module is the availability of various energy resources, which is driven by depletion and technology development (Fig. 2). Technology development is introduced in the form of learning curves for most fuels and renewable options. Costs decrease endogenously as a function of the cumulative energy capacity (learning rate), and in some cases, assumptions are made about exogenous technology change. Depletion is a function of cumulative production in the case of fossil fuels and nuclear feedstock and annual production in the case of renewables,

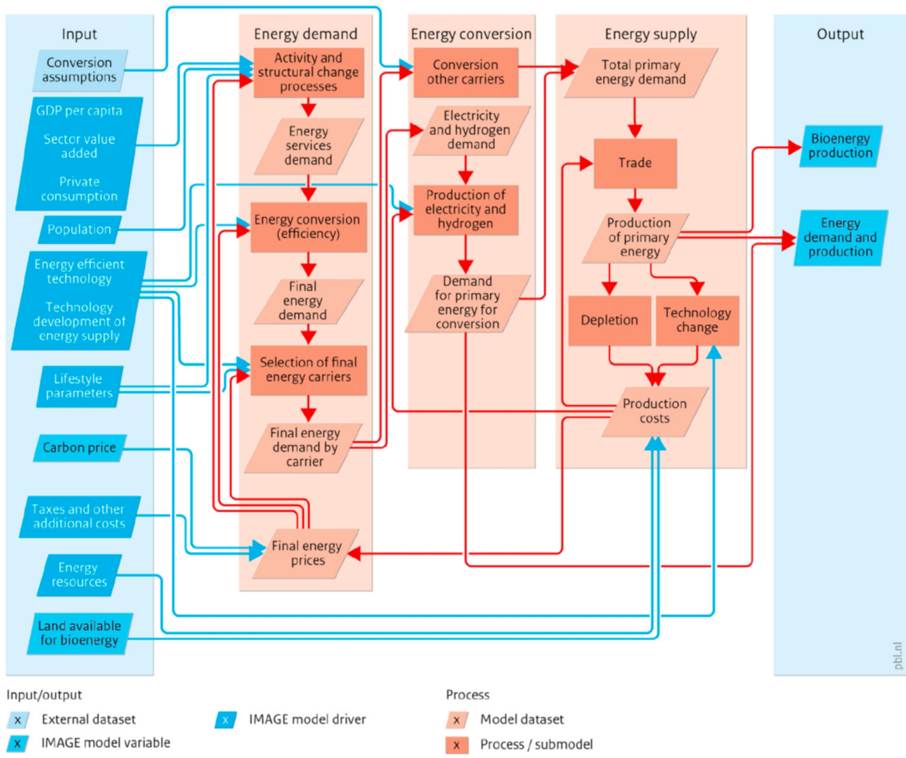

Fig. 1. Flow diagram of the TIMER energy demand and supply model. Source [30].

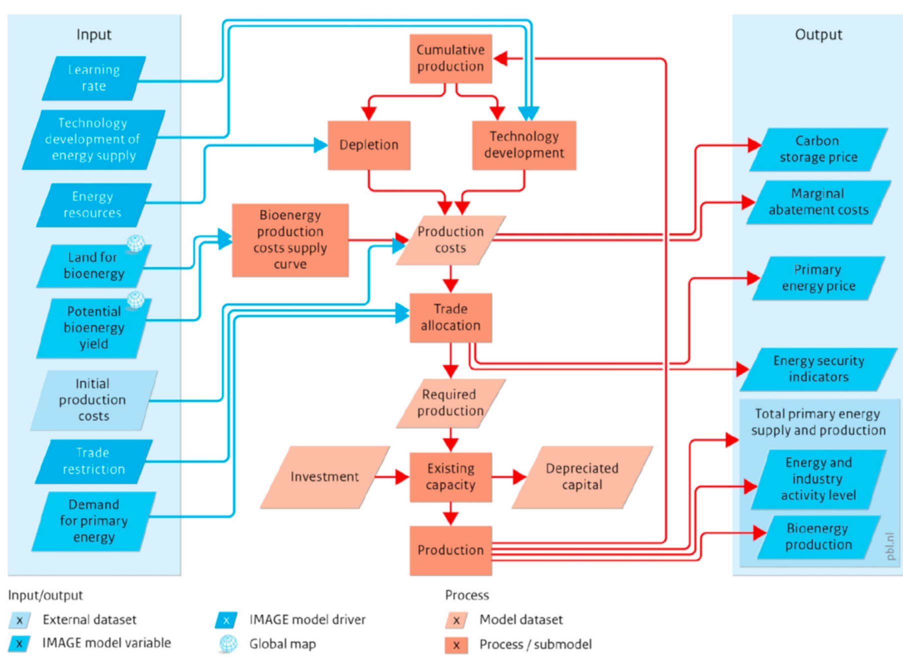

Fig. 2. Flow diagram of the energy supply model. Source [30].

where attractive production sites are used first. For each region, there are 12 resource categories for oil, gas and nuclear fuels, and 14 categories for coal. Each category has its own specific production costs based on long-term cost-supply curves per region [34]; the impact of uncertainties in fossil fuel availability is discussed in the discussion section. The impact of depletion and technology development lead to changes in primary fuel prices, which influence investment decisions in the energy demand module. The available land for bioenergy production is determined by the IMAGE land use model and restricted by the assumption that bioenergy crops can only be cultivated on abandoned agricultural land and on part of the natural grassland.

It is assumed that all demand is always met. Because regions are usually unable to meet all of their own demand, primary energy carriers, such as coal, oil and gas, are widely traded. Fossil fuels can be traded globally. The amount of fuel traded between regions depends on the relative production costs and those in other regions, augmented with transport costs, using multinomial logit equations (the development of these costs over time are provided in supplementary Excel files). Cartel behaviour is accounted for by assuming that regions that can supply at much lower costs than the average global production costs supply the fossil fuel at a price only slightly below the production costs of the importing regions. Loosening this assumption will affect trade, especially leading to more fossil fuel use early in the baseline (fossil fuels become cheaper for importing regions, although this also leads to faster depletion). The impact on the mitigation scenarios is much smaller, as fossil fuel use is restricted by the climate targets (it leads to somewhat more fossil fuel use with CCS relative to renewables). The model only considers trade between the 26 world regions in the IMAGE model, i.e. trade flows within world regions are not taken into account. Fossil fuels are traded in their primary energy form, and the refinery is assumed to take place in the importing region. Bioenergy is converted before the trade, and hence secondary energy volumes are used for this energy carrier. Electricity is assumed not to be traded among regions, except between the USA and Canada.

The emissions resulting from energy supply and land-use changes are used to calculate global mean temperature change using a slightly adapted version of the MAGICC 6.0 climate model [35].

Although calculations are done for 26 world regions, we have aggregated them to 16 regions here to more easily present results (i.e. net trade values of aggregated regions are shown). We also limit the time horizon to 2050, although the scenarios run until 2100.

2.2. Scenarios

All scenarios were based on the IMAGE implementation of the SSP2 baseline scenario. The SSP2 scenario describes a middle-of-the-road scenario in terms of economic and population growth and other long-term trends, such as technology development [36]. The mitigation scenarios have been constructed using the same method as in Van Vuuren et al. [23]. Two radiative forcing targets are analysed: 1.9 W/m^2 in 2100, representing a 1.5 °C target and 2.6 W/m^2 in 2100, representing a 2 °C target.

In all scenarios, these goals are achieved by introducing a universal carbon price in all sectors and regions from 2020 onwards. Before 2020, all mitigation scenarios have assumed the full implementation of the countries' reduction proposals (conditional pledges) for 2020, as part of the Cancun Agreements (based on Hof et al. [37]. The scenarios differ with regard to assumptions on lifestyle change and electrification rates and penetration of intermittent renewables in the energy system.

Table 1summarises the most important characteristics of the different scenarios and Table SI.1 in the Supplementary describes the characteristics in more detail. The *Carbon tax* scenario is based on the same assumptions regarding lifestyle change and technology as in the baseline, but where a carbon tax leads to different investment choices leading to lower emissions.

Additional to the carbon tax, the 2.0 and 1.5 °C *Lifestyle focused* scenarios reflect the possibility that environmentally friendly and resource-efficient modes of living are adopted by a majority of the population worldwide. These scenarios include assumptions on dietary change, food waste reduction, transportation, and residential energy use – assumptions which mainly affect behaviours and emissions in developed countries. For dietary change, we assume a quick transition to a healthier diet (the so-called Wilett diet) between 2020 and 2050, with low levels of meat consumption: 10.4 kcal/cap/day of cattle, 16.0 of pork, 32.3 of eggs, 33.2 of poultry and 13.0 of fish and seafood [38]. Food waste as fraction of total demand is also reduced in households (10% less avoidable waste per year starting in 2011, reaching 98% reduction in 2050), and in storage and distribution systems (5% less waste per year starting in 2011, reaching 86% in 2050). The absolute amount of food waste will decrease less quickly, since total demand increases with population size and affluence [39]. For transport, the scenarios assume a different relationship between income and transport volume, leading to changes in the preferred transport mode and traffic volume. This enforces a shift away from increasing private vehicle use to mass transit options (i.e. public transport) or non-motorized options (walking, biking). Furthermore, a gradual curtailment of long-distance trips (reducing, for example, the extent of air travel demand) is assumed. For residential energy use, the scenarios include assumptions on (water) heating behaviour and appliance energy use. To curtail heating demand, the scenario sets a limit on the floor space per capita (40 m^2/cap for urban households and 50 m^2/cap for rural households). Moreover, the base temperature is adapted downward by 1 °C in the case of heating and upward by 1 °C in the case of cooling. Water heating demand is reduced by assuming reduced shower time of 25%. Household electricity demand is curtailed by capping appliance ownership rates to the 2010 values in current high-income countries and by gradually phasing out tumble dryer for a washing line. We also assume environmentally conscious behaviour in domestic appliance use, e.g. by switching off stand-by modes and smarter use of appliances. This is represented via deducting stand-by energy consumption values from modelled appliances and implementing best available technology energy consumption values. A more detailed description of this scenario can be found in van Sluisveld et al. [22].

The 2.0 and 1.5 °C *Renewables focused* scenarios assume rapid electrification in the demand sectors, combined with low integration challenges for renewable energy due to optimistic assumptions about flexibility provision, grid expansion and storage. Electrification of demand sectors is achieved by either stimulating the use of electricity by introducing cost reductions for electricity (industry) or disallowing the use of non-electric technologies (transport and residential sector). Globally, the electricity shares in end use increase 48% for residential, 33% for transport and 47% for industry (starting from 21% to 26% today). We assume that for freight and air travel, hydrogen-based modes become available in the long-term. The penetration of intermittent renewable electricity options (wind and solar) in the power sector is increased by reducing the integration constraints following a different setting in the available dataset [40]. In addition, conditions for early retirement of fossil power capacity are relaxed and power sector foresight on carbon price development is increased.

The additional assumptions in the Lifestyle focused and Renewables focused scenarios lead to additional emission reductions. This additional "emission space" was used to limit the use of BECCS using the following method. First, for each alternative scenario, the assumptions in Table S1 were implemented in the baseline scenario, leading to direct impacts on emissions, energy and land use. Subsequently, the scenarios were combined with the carbon price trajectory of the 2 °C and 1.5 °C *Carbon tax* scenarios. Given the additional reductions obtained by the implemented measures from Table S1, the alternative scenarios overachieved the 2 °C and 1.5 °C targets. Subsequently, an additional "BECCS-price" was introduced in order to reduce BECCS. The "BECCS-price" was implemented in 2020 and held constant throughout the rest of the century. In order to find the right price level, it was increased in small steps to find the point where the 2100 forcing of the scenario was equal to 2.6 and 1.9 W/m^2. An alternative simpler methodology to reduce BECCS

Table 1
Scenarios included in this study.

Name (abbreviation)	Description	Climate target
Baseline (BL)	IMAGE implementation of the SSP2 scenario, in which a continuation of changes in lifestyle and technology trends as observed in the recent past is assumed.	
Carbon tax (Tax)	Climate policy is implemented by introducing a uniform carbon tax in all regions and sectors from 2020 onwards.	2 °C; 1.5 °C
Lifestyle focused (Tax + LS)	Next to the same uniform carbon tax as in the *Carbon tax* scenario, consumers change their habits towards a lifestyle that leads to lower GHG emissions. This includes a less meat-intensive diet (conforming to health recommendations), less CO_2-intensive transport modes (following the current modal split in Japan), less intensive use of heating and cooling (change of 1 °C in heating and cooling reference levels) and a reduction in the use of several domestic appliances. The additional reductions achieved with these measures are used to decrease the use of BECCS.	2 °C; 1.5 °C
Renewables focused (Tax + Ren)	Next to the same uniform carbon tax as in the *Carbon tax* scenario, higher electrification rates in all end-use sectors are assumed, combined with optimistic assumptions on the integration of intermittent renewables and on costs of transmission, distribution and storage. The additional reductions achieved with these measures are used to decrease the use of BECCS.	2 °C; 1.5 °C

would be to simply exclude BECCS completely from the scenarios, but with such a restriction the 1.5 °C would not be feasible anymore according to our model.

2.3. Energy diversity and sovereignty

In describing energy security, many perspectives and associated indicators have been identified in literature [4,5,41,42]. As explained in the Introduction, Kruyt et al. [5] suggested several indicators classified according the four dimensions as defined by the Asia Pacific Energy Research Centre [42] availability, accessibility, affordability, and acceptability. Of these four dimensions, we take the same approach as Jewell et al. [4] and focus on indicators related to accessibility, as these are the most interesting indicators when comparing different mitigation scenarios in the same socio-economic context. Two major aspects of energy accessibility are diversity of energy supply and energy sovereignty. We have selected indicators for both these aspects based on the overlap in terms of our modelling framework. Table 2 summarises the indicators used in this study.

For diversity of energy supply, we use the same adapted version of the Shannon Diversity Index as used by the Asia Pacific Energy Research Centre [42]:

$$Energy\ Diversity\ Indicator = -\frac{\sum_{i=1}^{n}(p_i \ln(p_i))}{\ln(n)}$$

where pi is the share of the primary energy carrier i in the total primary energy supply and n is the total number of primary energy carriers. We here distinguish between the energy carriers oil, gas, coal, bioenergy, solar, wind, nuclear and hydro, with all other energy carriers grouped in one category “others”. This indicator is a normalised Shannon Diversity Index, where a value of 1 indicates perfect diversity (all energy carriers have the same share in total primary energy) and a value of 0 implies that a region is dependent on a single energy carrier. For the energy sources solar, wind, nuclear and hydro, we do not apply conversion rates, so that primary energy is equal to final energy. In the mitigation scenarios, CCS is applied on a share of the fossil fuels and bioenergy - but we do not regard this as separate energy source for calculating the diversity.

All other indicators used in this study refer to energy sovereignty, which is strongly related to energy trade. The most aggregate indicator for energy sovereignty is the total volume of energy traded globally, both in absolute volumes and relative to total primary energy use. Here, we consider oil, coal and gas trade in their primary energy form. Bioenergy is converted before trade and hence secondary energy volumes are used for this energy carrier (also see Section 2.1).

The diversity of energy-exporting regions is an important indicator for the degree to which importing regions are dependent on a selected set of countries for their imports. Both the number of countries as well as their characteristics (e.g. in terms of stability) are important to consider here. While we do not explicitly assess the second aspect, we do specifically take into account which regions are exporting the energy carrier in the scenarios. Regarding diversity in energy export, we use the same adopted version of the Shannon Index as used for energy diversity – only here, pi refers to the share of region i in the global export of the energy carrier and n refers to the total number of regions which theoretically could be export that energy carrier (in our case, n is equal to the total number of regions considered minus one, which is 15).

The final important indicator we consider for energy sovereignty relates to import dependency. For this, we relate the share of oil, gas, coal, and bioenergy in total energy use with the net imports of these fuels as share of total use. This strongly relates to the Net Energy Import Dependency indicator used by the Asia Pacific Energy Research Centre [42]; only here, we disaggregate the indicator by its components to provide more insight into the drivers of change.

Table 2
Indicators of energy security used in this study.

Dimension	Indicator
Energy diversity	Normalised Shannon Index for diversity in primary energy mix
Energy sovereignty	Volume of absolute energy trade by energy carrier
Energy sovereignty	Energy trade relative to energy use (total and for individual energy carriers)
Energy sovereignty	Normalised Shannon Index for energy export diversity by energy carrier
Energy sovereignty	Energy import dependency by energy carrier: import as share of consumption combined with share in total primary energy

3. Results

First, we discuss the scenarios in terms of GHG emissions and energy mix. Subsequently, the results are presented in terms of the diversity in the primary energy and the role of energy trade.

3.1. GHG emissions and primary energy mix

In the baseline scenario, total GHG emissions increase from 52 to 74 Gt CO_2eq between 2015 and 2050. This increase is predominantly attributable to CO_2 emissions from energy use, which increase from 35 to 48 Gt CO_2 (left panel of Fig. 3). The baseline GHG emission level of SSP2 of all six integrated assessment models in the SSP database (https://tntcat.iiasa.ac.at/SspDb) ranges from 74 to 84 Gt CO_2eq by 2050, meaning that IMAGE is on the lower side of the range.

By definition, all mitigation scenarios show large emission reductions by 2050 compared to baseline. The largest reductions occur in CO_2 emissions from the energy-sector. While also methane (CH_4), nitrous oxide (N_2O) and fluorinated gas (F-gas) emissions are reduced, their reductions are smaller in absolute terms, given the smaller share in baseline emissions. The mitigation strategy assumptions (*Carbon tax, Lifestyle focused* or *Renewables focused*) strongly impact the mix of GHG reductions. Compared to the *Carbon tax* scenario, the net CO_2 emissions are higher in the *Lifestyle focused* scenarios and lower in the *Renewables focused* scenarios. In the *Lifestyle focused* scenario, a decrease in meat consumption limits CH_4, N_2O and land-use related CO_2 emissions. Subsequently, the need for mitigation in the energy system is reduced, which leads to higher energy CO_2 emissions. In the *Renewables focused* scenario, mitigation is predominantly achieved in the energy system, resulting in lower energy CO_2 emissions. The largest difference between the 2 °C and 1.5 °C scenarios is that the latter scenarios show lower energy CO_2 emissions by 2050. In the *Carbon tax* and *Renewables focused* 1.5 °C scenarios, CO_2 emissions are even net-negative in 2050.

In the *Baseline* scenario, global primary energy use increases by 49% between 2015 and 2050, with the share of fossil fuels remaining about the same (middle panel of Fig. 3; Figure SI.2 shows more detailed global results with CCS). The primary energy mix differs substantially between world regions, with a relative high share of coal in India and China, a relative high share of gas in Russia and the Middle East/North Africa and Canada, a relative high share of oil in Japan, the Middle East/North Africa and Latin America, and a relative high share of bioenergy in Sub-Saharan Africa and Brazil (Figure SI.4 shows detailed results for all 16 world regions). In the mitigation scenarios, primary energy use is 40–50% lower than in the baseline, with a strongly different energy mix.

All mitigation scenarios show a strong decline in fossil fuels, between 37% in the 2 °C *Lifestyle focused* scenario to 66% in the 1.5 °C *Renewable* scenario in the period 2015–2050. Coal is strongly reduced in all mitigation scenarios, and most of the coal still used is equipped with CCS (see Figure SI.2). The amount of oil used differs among the mitigation scenarios: the share of oil in the total energy mix is still about 20% in the *Carbon tax* and *Lifestyle focused* 2 °C scenarios, but much lower in all other scenarios. In these other scenarios, hydrogen and electricity are the main energy carriers in transport by 2050 (see Figure SI.3).

The use of bioenergy increases in all scenarios, but to different degrees and for different uses. The *Carbon tax* and 1.5 °C scenarios show the highest bioenergy shares, with up to 40% in the 1.5 °C *Carbon tax* scenario (compared to 29% in the 2 °C *Carbon tax* scenario and 11% in 2015). The *Lifestyle focused* scenarios show the lowest bioenergy shares of around 20%. In the 1.5 °C *Carbon tax* and *Renewables focused* scenario, bioenergy is mainly used in combination with CCS for carbon dioxide removal. In the 2 °C *Carbon tax* and *Lifestyle focused* scenario, bioenergy (mainly lignocellulosic) is used extensively in transport. The 1.5 °C *Lifestyle focused* scenario most strongly limits bioenergy use. This is partly due to a reduced requirement for mitigation in the energy sector, made possible by the assumed lifestyle changes. The 2 °C *Renewables focused* and all 1.5 °C scenarios are further characterised by strong electrification of the energy system, as shown in the right-hand graph of Fig. 3.

The more optimistic assumptions for intermittent renewables in the *Renewables focused* scenario results in much higher intermittent renewables shares (about 30% compared to about 10% in the other mitigation scenarios) and much lower low BECCS use in the 2 °C scenario. Due to the stronger efforts required in the 1.5 °C scenario, BECCS still is an important measure in the 1.5 °C *Renewables focused* scenario, however.

3.2. Energy diversity

By 2050, the diversity in the primary energy mix, expressed as a normalised Shannon diversity index as explained in the Methods section, is in almost all regions higher in the mitigation scenarios

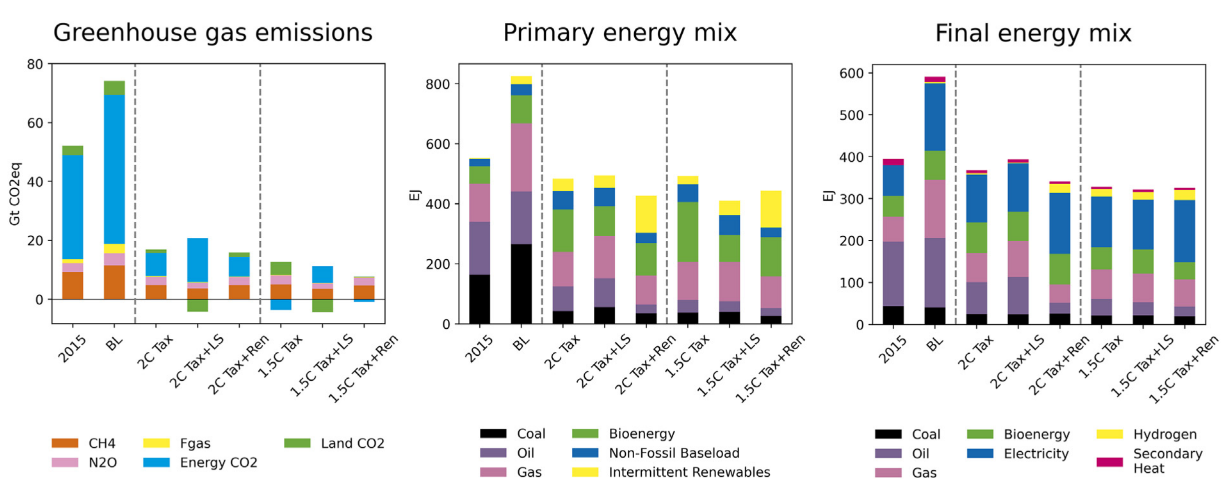

Fig. 3. Global GHG emissions per emissions category, primary energy mix and final energy mix, 2015 and 2050. Fossil fuels and bioenergy include with and without CCS. Secondary heat refers to heat centrally generated by either combined heat and power plants or heat plants. Figure SI.2 provides more detail on the primary energy mix, Figure SI.3 provides more detail on the final energy mix of transport and Figure SI.4 provides detailed energy mixes for 16 world regions.

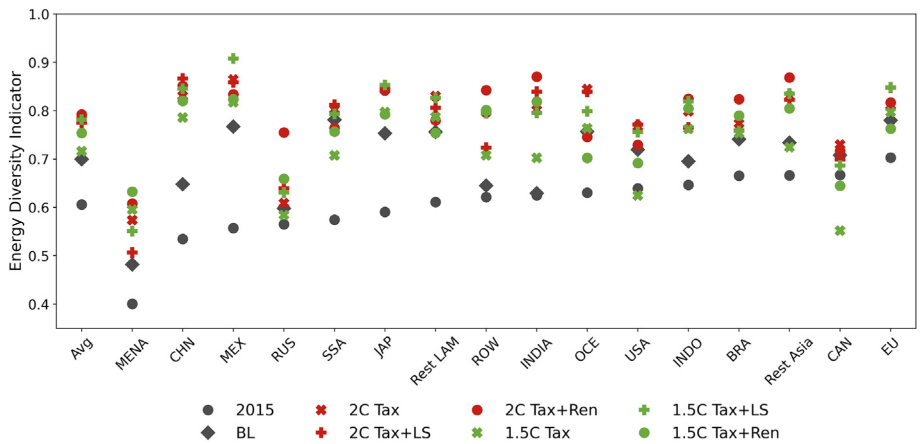

Fig. 4. Diversity in primary energy mix, 2015 and 2050. Regions/countries are ordered according to their diversity in 2015: MENA: Middle East and North Africa, RUS: Russian Federation, CHN: China, SSA: Sub-Saharan Africa, MEX: Mexico, ROW: Rest of the world, Rest LAM: Rest of Latin America, OCE: Oceania, JAP: Japan, INDO: Indonesia, CAN: Canada, EU: Europe, BRA: Brazil. Avg is average of all world regions. The Energy Diversity Indicator is a normalised Shannon Index as explained in the methods section. A value of 1 indicates perfect diversity (all energy carriers have the same share in total primary energy) and a value of 0 implies that a region is dependent on a single energy carrier.

than in both 2015 and baseline 2050 levels (Fig. 4). This is due to the strong dominance of fossil fuels in the baseline. The only regions for which the diversity by 2050 is lower than in 2015 in some mitigation scenarios are Canada and the USA. In Canada, the 1.5 °C scenarios — and especially the *Carbon tax* one where BECCS is not limited — show low diversities due to the strong dependence on only three energy types (bioenergy, natural gas, and hydro, see Figure SI.4). The USA also shows a low diversity for the 1.5 °C *Carbon tax* scenario, as in this scenario its energy system is largely dependent on bioenergy and natural gas.

For most regions, the different scenarios lead to very different levels of energy diversity. This is especially the case for Canada, Russia, and India. On average, the 1.5 °C *Carbon tax* mitigation scenario shows the lowest diversity of the mitigation scenarios. This scenario is strongly dependent on bioenergy (both with and without CCS) and is relatively conservative on the use of intermittent renewables. The energy diversity of the 1.5 °C *Renewables focused* scenario is also relatively low, as the energy mix is largely based on intermittent renewables, gas, and bioenergy. The 1.5 °C *Lifestyle focused* scenario has a similar improvement in energy diversity as the 2 °C scenarios, given the balanced use across different energy sources.

On average, all 2 °C scenarios show similar energy diversity levels, but there are significant differences across regions: India and China show the largest differences between baseline and mitigation scenarios, making mitigation in these countries more interesting for diversification.

3.3. Energy sovereignty

For energy sovereignty, we first look at global absolute and relative energy trade, followed by energy export diversity and energy import dependency. Hydrogen can be traded, but the volumes of traded hydrogen are so low that we do not report this separately. Figures SI.9-SI.12 provide detailed results of energy trade by fuel and scenario in the form of Sankey diagrams; here, we focus on indicators more directly related to energy sovereignty.

3.3.1. Global energy trade

In the baseline scenario, energy trade increases from 130 EJ in 2015 to 270 EJ in 2050, predominantly by increasing trade in fossil fuels (left panel of Fig. 5). Depending on the mitigation scenario, the traded volume either increases slightly or decreases significantly compared to 2015. This is in line with the findings of Cherp et al. [10]; who find starkly decreasing trade in coal and oil in default mitigation scenarios and increasing trade in gas (but at lower rates than baseline).

Scenarios with more energy efficiency improvement or more intermittent renewables (both *Renewables focused* scenarios and the 1.5 °C *Lifestyle focused* scenario) show the lowest total energy trade. The trade in bioenergy increases in all mitigation scenarios, and especially in the *Carbon tax* scenarios.

For each energy carrier, trade as share of total use increases significantly in all scenarios (right panel of Fig. 5). In relative terms, oil trade is by far the highest: more than 60% of total oil use is traded in all scenarios. For gas, this around 35% in all scenarios and for coal about 25%. The relative trade in bioenergy is more strongly scenario-dependent: in the 1.5 °C *Lifestyle focused* scenario, in which bioenergy use is strongly limited, only about 15% of bioenergy is traded. In the 2 °C scenarios, this is twice as high.

These results show that globally, energy trade is lower in mitigation scenarios than in the baseline scenario, which generally improves energy sovereignty. This effect is especially strong in all 1.5 °C mitigation scenarios and the 2 °C *Renewables focused* scenario: in these scenarios oil (most traded) is phased out more quickly. A shift from natural gas to bioenergy does not lead to an improvement in sovereignty in 2 °C scenarios, as the share of these fuels being traded is about equal. Also important to note is that while total relative energy trade declines in all scenarios compared to baseline, it only declines compared to 2015 levels in the *Renewables focused* scenarios. Less than 20% of all energy use is traded in these scenarios, compared to 22% in 2015 and 32% in the baseline.

3.3.2. Diversity in energy exporters

Currently, total diversity of energy exporters is very low: oil is responsible for about 70% of total energy trade and the Middle East and North Africa are the main exporting regions for oil (Fig. 6; orange triangles show Shannon's diversity index). The diversity of gas and coal exporters is higher, but their total share in energy trade is limited. The trade in bioenergy is currently marginal compared to the trade in other fuels.

In the baseline scenario, the diversity of oil exporters increases. However, the diversity of gas exporters decreases, as the large increase in gas use is largely met by Russia and the Middle East and North Africa (also see Figure SI.9). Coal and bioenergy show the

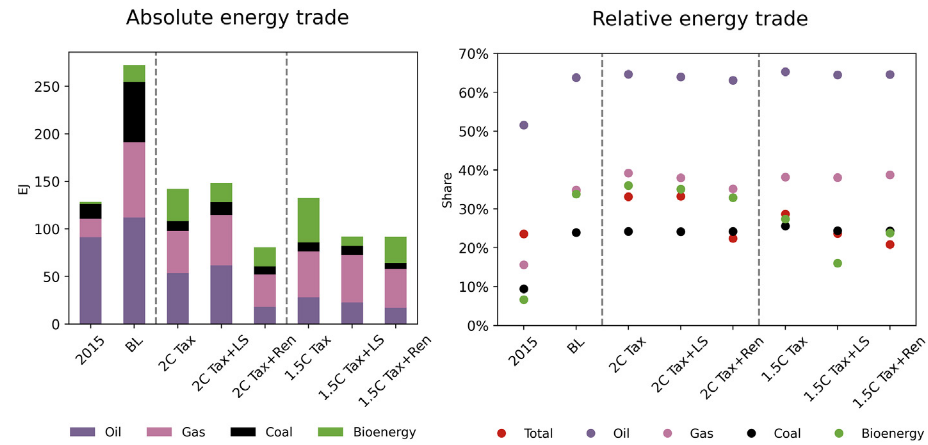

Fig. 5. Global absolute and relative energy trade, 2015 and 2050. Relative energy trade is defined as the volume of trade of the energy carrier as share of total use of the energy carrier. Detailed trade flows between regions are provided in Sankey diagrams in Figures SI.9-SI.12.

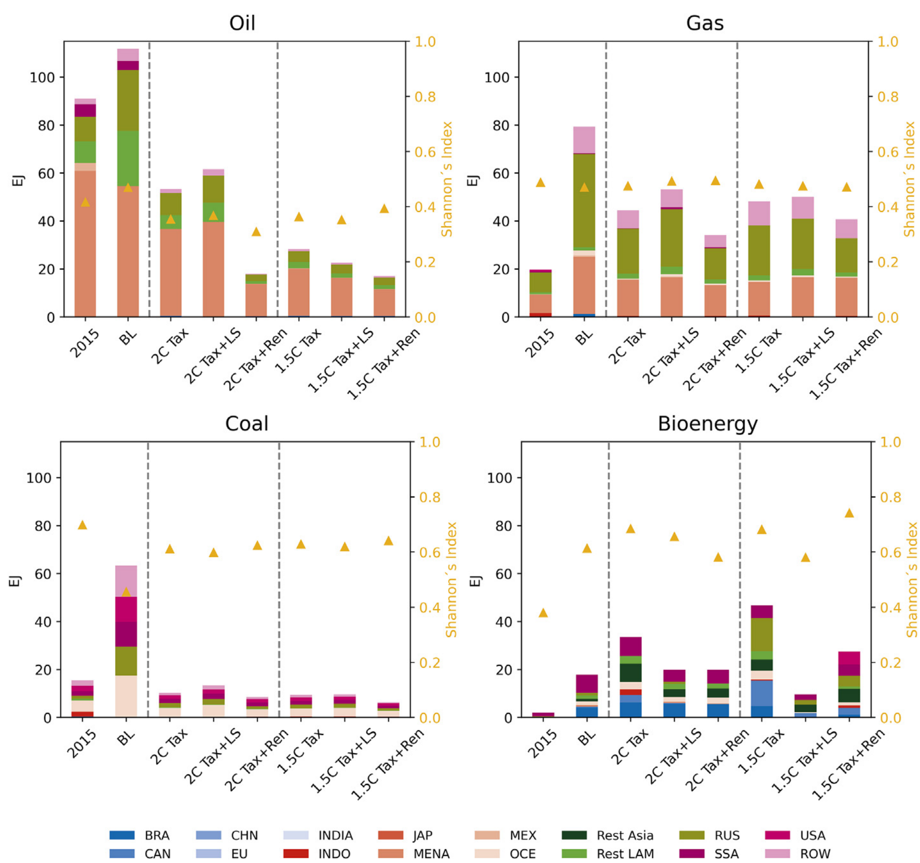

Fig. 6. Regional diversity in energy exporters, 2050. Regions/countries: BRA: Brazil, CAN: Canada, CHN: China, EU: Europe, INDO: Indonesia, JAP: Japan, MENA: Middle East and North Africa, MEX: Mexico, OCE: Oceania, Rest LAM: Rest of Latin America; RUS: Russian Federation, SSA: Sub Saharan Africa; ROW: Rest of the world. Triangles indicate the values for the normalised Shannon's Index (right y-axis). A value of 1 indicates perfect diversity (all exporters have the same share in total exports) and a value of 0 implies that there is only 1 exporter. Only regions with net exports are shown.

highest diversity in exporters.

There is not much difference in diversity of gas and coal exporters between the scenarios (also see Figures SI.10 and SI.11). The diversity of coal exporters is very high, as coal is abundantly available. The diversity in gas exporters is much lower, as the Middle East, North Africa and Russia are responsible for the lion's share of total gas exports. The differences in diversity of bioenergy exporters are much larger between scenarios, as this is driven by the scenario-dependent assumptions on land availability for bioenergy production [43]. In the 2 °C scenarios, the largest share of bioenergy is provided by tropical regions in Sub-Saharan Africa, Brazil and the Rest of Asia (also see Figure SI.12). The largest need for bioenergy is in the 1.5 °C *Carbon tax* scenario. As a result, forest areas in temperate boreal regions are also used for bioenergy production [44]. This is reflected by large bioenergy exports by Canada and Russia in this scenario. The 1.5 °C *Lifestyle focused* scenario, and to a lesser extent the 1.5 °C *Renewables focused* scenario, are able to avoid this.

The trade in coal decreases strongly in the mitigation scenarios, which has a negative effect on overall diversity of energy exporters as the diversity of coal exporters is very high. This is partly compensated by increased bioenergy trade, which in four of our six mitigation scenarios show a larger diversity of exporters than coal. In contrast to oil and gas, more bioenergy trade means that more regions export bioenergy, and higher trade therefore can lead to higher diversity. Indeed, the three scenarios with the largest bioenergy trade have the highest regional diversity in bioenergy exports (Export Diversity Indicator in right panel).

3.3.3. Energy imports

The dependency on fuel imports depends on both the share of the fuel in total primary energy of a region and the share of that fuel being imported. These two indicators are mapped out against each other in Fig. 7. Only the averages of all importing regions for each scenario are plotted, as this is easier for extracting general conclusions. The results for all individual regions can be found in the SI (Figures SI.5-SI.8). The two indicators determine energy security risks: If an energy carrier is only a small share of the total mix, risks are low, and if only a small share of that fuel is imported, risks are also low. This means that risks are lowest in the bottom-left corner and highest in the top-right corner.

The share of oil in the mitigation scenarios decreases compared to baseline, especially in all 1.5 °C and the 2 °C *Renewables focused* scenarios. Countries that import oil are on average dependent on more than 80% on those imports in all scenarios. This means that oil import dependency only decreases in scenarios in which oil use itself is decreased. In the 2 °C *Carbon tax* and *Lifestyle focused* scenarios, oil import dependency remains almost as high as in the baseline scenario.

Both the share of gas in total primary energy use and the share of gas being imported does not differ as much between the scenarios compared to the other fuels. While in absolute terms, gas use decreases in the mitigation scenarios, the relative share does not change that much. The 1.5 °C scenarios do show a lower import dependency on gas, which is due to a lower absolute use.

The share of coal decreases drastically in all mitigation scenarios and the import dependency increases: about 50%–60% of the coal used is being imported in 2050. This is a similar share as gas, but as gas has a much higher share in the total energy mix, the import dependency of coal is lower than that of gas.

The share of bioenergy in total primary energy use increases strongly in the *Carbon tax* and the 1.5 °C *Renewables focused* scenarios. The average share that is imported is significantly lower than oil and gas, however: in all scenarios, less than half of bioenergy use is being imported. The dependency in imports is especially low in the 1.5 °C *Lifestyle focused* scenario.

4. Discussion

This paper presented implications for the energy security of 2 °C and 1.5 °C pathways for sixteen countries or world regions. More specifically, the implications for energy diversity and total energy trade and (diversity in) energy imports and exporters were analysed.

Energy security is a broad concept encompassing physical, economic, political, and environmental aspects. We focused on indicators that provide information on the vulnerability of energy systems, emphasising that higher diversities of fuel mix and energy exporters and lower dependencies on energy imports (i.e. higher energy sovereignty) lead to lower vulnerability. Diversity in the fuel mix is not an objective in itself and may even be at odds with achieving ambitious climate targets. Still, it is important to be aware of the consequences of achieving ambitious climate objectives on the vulnerability of the energy system.

The indicators we chose for measuring the vulnerability of a region's energy system are clearly not sufficient to provide a total picture of energy security implications. Perhaps most importantly, the risk of being dependent on imports not only depends on the

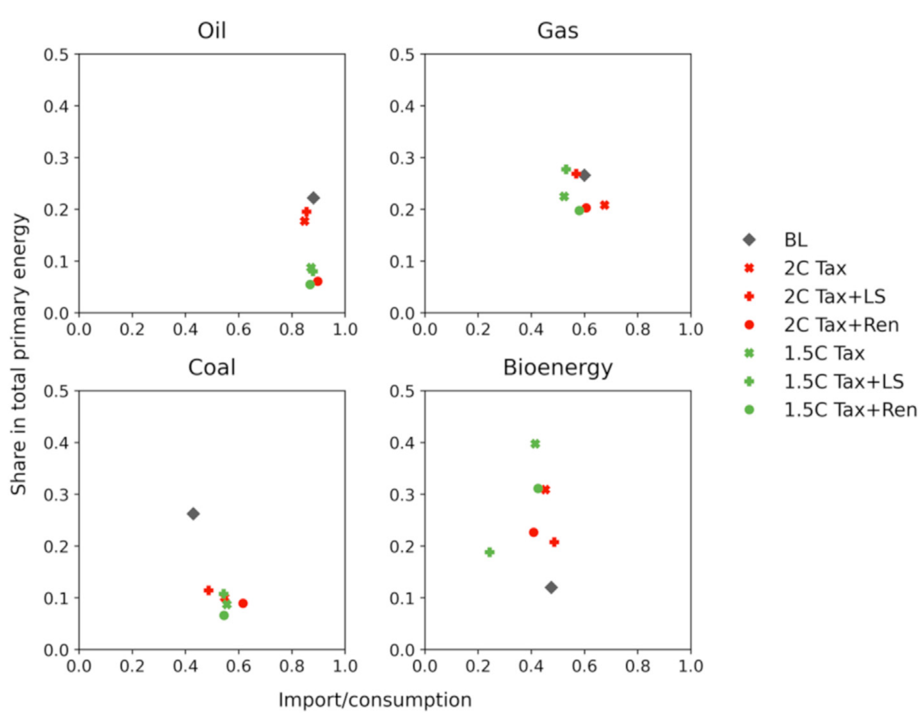

Fig. 7. Energy import dependencies, 2050. The markers indicate the average values of 16 world regions. Import dependencies by region are provided in Figures SI.5-SI.8.

number of exporting regions but also on geopolitical considerations and the social, political, and economic stability of these regions (there is a very low diversity in oil and gas exporters in all scenarios with the Middle East, North Africa, and Russia as main players). Although we have presented results for 16 world regions, it is difficult to assess this latter aspect given our time horizon of 2050. Still, vulnerability is not only dependent on the regional diversity of energy exporting countries and the dependency on imports for fuels but also global socio-economic developments. In a world with global cooperation and prosperity, being dependent on imports involves fewer risks than in a world with a lot of conflicts.

Each technology to generate energy has its disadvantages and challenges, which also affects energy security and vulnerability. This is especially the case for bioenergy, for which concerns have been raised related to its energy return on investment and risks for food production and biodiversity [16,17]; also see Introduction). While we have not explicitly developed scenarios that limit bioenergy, we find that the scenarios in which BECCS is limited also shows less bioenergy. This means that, according to our model, bioenergy is especially interesting in combination with CCS to generate negative emissions. We have not assessed the impact of larger shares of bioenergy on food security, but compared to other models, IMAGE is conservative in bioenergy use [45]. Possible reasons for this are that i) first-generation biofuels are not used in the scenarios (even though they are part of the technology portfolio) due to their poor energy return on investment, ii) IMAGE takes biophysical limits explicitly into account by putting explicit limits on deforestation from bioenergy and uses a “food first” principle when determining land availability for energy-crops [46,47].

In setting up our scenarios, we aimed to cover a wide range of strategies to achieve the Paris climate objectives, focusing on strategies to limit the use of BECCS. Indeed, the scenarios lead to very different primary energy mixes: by 2050, the share of bioenergy ranges from 20% to 40% across the scenarios; the share of intermittent renewables from 8% to 29%, and the share of nuclear and hydro from 7% to 16%. While this does not cover the full range of 85 1.5 °C scenarios as assessed by the IPCC in its Special Report on 1.5 °C [3]; in which ranges of intermittent renewables of 4%–52% and bioenergy of 10%–54% are reported, we feel that our scenarios are sufficiently heterogeneous to provide insight into the effect of different strategies on energy diversity and sovereignty.

While we specifically developed scenarios in which BECCS use was reduced, all scenarios still show a substantial deployment of BECCS and CCS. In our 2 °C *Carbon tax* scenario, 8.2 Gt CO_2 is captured by CCS annually by 2050, which is reduced to 5.0 Gt CO_2 in the 2 °C *Lifestyle focused* scenario and 4.1 Gt CO_2 in the 2 °C *Renewables focused* scenario. These numbers are substantially lower than the averaged CO_2 captured in 2050 of 9.7 Gt CO_2 for 116 2 °C scenarios in the 1.5 °C scenario explorer [48]. For 1.5 °C scenarios, the amount of CO_2 captured is higher: 16.4, 7.1 and 10.1 Gt CO_2 for the 1.5 °C *Carbon tax*, *Lifestyle focused,* and *Renewable focused* scenario, compared to an average of 85 1.5 °C scenarios of 11 Gt CO_2. The degree to which these CCS deployment rates are feasible depends on social, technological, and economic circumstances. To illustrate this, Koelbl et al. [49] used the same model framework as used in our paper to analyse the impact of techno-economic uncertainty on CCS deployment. They found that cumulative CO_2 captured until 2050 ranges from 76 to 253 Gt in 2 °C scenarios, depending on CCS techno-economic parameter settings. In our set of scenarios, this ranges from 65 Gt in the 2 °C *Lifestyle,* and *Renewable focused* scenarios to 215 Gt in the 1.5 °C *Carbon tax* scenario. An equally important question is whether 2 °C scenarios *without* CCS are feasible. In a multi-model comparison study, Krey et al. [50] found that only four out of eleven Integrated Assessment models found feasible pathways for 2 °C if CCS in the technology portfolio is excluded. These four scenarios showed an increase in cumulative mitigation costs by, on average, a factor of 2.5. The total set of 200 2 °C and 1.5 °C scenarios in the 1.5 °C scenario explorer includes only one scenario without CCS. This scenario assumes very low global energy demand by 2050 [20]. The number of scenarios without BECCS is larger, but still somewhat limited: 17 out of 200 scenarios show no BECCS use in 2 °C or more ambitious scenarios (five different IAMs developed these 17 scenarios).

The availability of fossil fuel resources is also a key uncertainty in scenario analysis. Compared to the Current Policies scenario of the IEA [51]; our baseline scenario shows less oil (−10% against +24% between 2018 and 2040) and gas (+44% against +50%) production, and more coal (+40% against +15%) production. This results from assumed resource availability (volume and cost) ad assumptions influencing the competitiveness of alternatives. The IMAGE resource assumptions are based on Rogner [34]. In the literature, both higher and lower estimates can be found. Based on an “ultimately recovery resources” approach, Capellán-Pérez et al. [52] concludes that fossil fuel depletion is only likely to occur in the second half of the century. However, Wang et al. [53] conclude that high baseline scenarios are unlikely due to fossil fuel resource constraints. They find probabilistic values of CO_2 concentrations of around 500 ppm in 2050, with total fossil fuel production in 2050 at about the same as the 2019 level. In our baseline scenario, CO_2 concentrations increase to 515 ppm by 2050, with total fossil fuel production being 30% higher than the level of 2019. Compared to Wang et al., our baseline scenario has a higher use of natural gas and coal. However, resource estimates by the USGS show that coal and natural gas resources are considerable. The estimates of Wang are not primarily based on available resources, however, but on actual production of fossil fuels in scenarios, including scenarios in which strong policies limit fossil fuel extraction (e.g. on Kharecha and Hansen [54]; in which fossil fuel extraction is constrained by a rising price on carbon emissions to discourage conversion of the vast fossil resources into useable reserves). In all our mitigation scenarios, the production of all fossil fuels remains well below the trends as provided by Wang et al. and also remain well below the available total resources. Therefore, it does not seem likely that uncertainty in fossil fuel availability significantly influences our results, especially not for our mitigation scenarios.

Finally, the scenarios that have been developed for this study have not taken into account the impact of the COVID-19 pandemic. While the short-term impacts are significant, COVID-19 is expected to have little effect on estimates for the diversity and sovereignty consistent for the 2 °C and 1.5 °C scenarios by 2050, as the short-term impact of the pandemic is not the result of structural changes and could be quickly reversed as lockdown measures are lifted. In its impact assessment for stepping up Europe's climate ambition for 2030, for instance, the European Commission estimates very small effects of COVID-19 on key energy indicators in 2030 and 2050 [55]. Furthermore, it is important to keep in mind that scenarios such as developed here are not predictions of what will happen, but should be regarded as explorations of different possible futures.

5. Conclusions

Taking the above discussion points into consideration, the following conclusions can be drawn from our analysis.

It is important to take energy security considerations into account when constructing climate mitigation scenarios. Energy security forms a central element of national energy strategies. Our study shows that energy diversity and sovereignty, both important aspects of energy security, differs substantially across different mitigation strategies and climate targets. Taking these aspects into account when constructing scenarios can therefore increase the policy relevance of such scenarios.

In almost all regions, energy diversity increases in mitigation scenarios relative to 2015. In the baseline, energy diversity increases due to lower reliance on fossil fuels and increasing shares of bioenergy and intermittent renewables. The mitigation scenarios show, for most regions, even higher growth of both bioenergy and intermittent renewables, which, together with much lower energy use and fossil fuel share in the energy mix, leads to higher diversity. The increase in energy diversity is especially large in China, Mexico, and Japan.

1.5 °C scenarios with extensive use of bioenergy show a lower energy diversity than 2 °C scenarios. Our *Carbon tax* 1.5 °C mitigation scenario shows extensive use of bioenergy. This leads to a lower energy diversity than the *Carbon tax* 2 °C scenario – and even a lower energy diversity than 2015 levels for the USA and Canada. In scenarios where bioenergy is lower – made possible by stronger lifestyle changes – there is not much difference in energy diversity between the 1.5 °C and 2 °C scenarios.

The share of energy traded decreases in all mitigation scenarios compared to the baseline, but only decreases compared to 2015 levels in scenarios with a strong focus on renewables. The strong absolute increase in energy trade in the baseline scenario is largely undone in all mitigation scenarios. However, only in the scenarios with a strong penetration of intermittent renewables there is a decrease in total absolute and relative energy trade compared to 2015. In other mitigation scenarios, coal trade decrease relative to baseline is largely compensated with additional trade in gas and bioenergy.

Import dependencies shift from Middle East, North Africa and Russia to a broader set of regions that produce bioenergy. In all mitigation scenarios, import dependence on coal and oil decreases sharply – especially in the 1.5 °C scenarios and 2 °C *Renewables focused* scenario. Total trade in gas increases relative to 2015 levels, but less than in baseline levels. Overall, this leads to less dependence on relatively few fossil-fuel exporting regions and more dependence on regions that can supply bioenergy (e.g. Sub-Saharan Africa, Brazil, USA, Canada, Russia, rest of Asia).

In contrast to oil and gas, more bioenergy trade does not necessarily lead to lower energy sovereignty. The regional diversity in bioenergy exports is higher than the regional diversity in fossil fuel exports. More bioenergy trade implies that it is profitable for more regions to export bioenergy, and higher trade can lead to higher diversity in exporters. Therefore, our scenarios with the most extensive bioenergy trade have the highest regional diversity in bioenergy exporters.

In general, climate policy increases energy diversity and sovereignty, but the degree to which is regionally-dependent and also depends on the chosen strategy. Mitigation strategies that focus on lifestyle changes and intermittent renewables generally involve a diverse mix of energy carriers that can be locally produced, leading to a higher increase in energy security than default mitigation strategies. This can be regarded as a co-benefit of such strategies. A strong focus on bioenergy could lead to similar energy dependencies as fossil fuels. However, the share of bioenergy in the total energy mix remains for most regions well below current oil and gas shares. The number of potential supplying regions is also larger for bioenergy than for oil and gas. This implies that even mitigation strategies, including on bioenergy score better on energy security than current energy systems.

Credit author statement

AH: Conceptualisation, Validation, Formal Analysis, Data Curation, Writing – Original Draft, Visualization, Supervision. KE: Conceptualisation, Formal Analysis, Data Curation, Writing - Review & Editing, Visualization. HSdB: Methodology, Writing - Review & Editing. VD: Methodology, Writing - Review & Editing. JCD: Methodology. MGJdE: Writing - Review & Editing. DEHJG: Methodology, Writing - Review & Editing. DPvV: Methodology, 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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.122197.

References

[1] Höhne N, et al. Emissions: world has four times the work or one-third of the time. Nature 2020;579:25–8.
[2] IPCC. In: Pachauri RK, Meyer LA, editors. Climate change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change [core writing team. Geneva, Switzerland: IPCC; 2014.
[3] IPCC. Global warming of 1.5°C: an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. The Intergovernmental Panel on Climate Change. 2018.
[4] Jewell J, et al. Energy security under de-carbonization scenarios: an assessment framework and evaluation under different technology and policy choices. Energy Pol 2014;65:743–60.
[5] Kruyt B, et al. Indicators for energy security. Energy Pol 2009;37:2166–81.
[6] European Commission. European energy security strategy. COM(2014; 2014. p. 330. final, https://www.eesc.europa.eu/resources/docs/european-energy-security-strategy.pdf.
[7] White House The. National security strategy of the United States of America. 2017 [Washington, DC].
[8] Winzer C. Conceptualizing energy security. Energy Pol 2012;46:36–48.
[9] APERC. A quest for energy security in the 21st century. Resources and constraints. Asia Pacific Energy Research Centre; 2007.
[10] Cherp A, et al. Global energy security under different climate policies, GDP growth rates and fossil resource availabilities. Climatic Change 2016;136:83–94.
[11] Rogelj J, et al. Mitigation pathways compatible with 1.5 C in the context of sustainable development. 2018.
[12] Bui M, et al. Carbon capture and storage (CCS): the way forward. Energy Environ Sci 2018;11:1062–176.
[13] Anderson K. Duality in climate science. Nat Geosci 2015;8:898–900.
[14] Anderson K, Peters G. The trouble with negative emissions. Science 2016;354:182–3.
[15] de Castro C, et al. A top-down approach to assess physical and ecological limits of biofuels. Energy 2014;64:506–12.
[16] Giampietro M, Mayumi K. The biofuel delusion: the fallacy of large scale agro-biofuels production. Routledge; 2009.
[17] Gomiero T. Are biofuels an effective and viable energy strategy for industrialized societies? A reasoned overview of potentials and limits. Sustainability 2015;7:8491–521.
[18] Van Vuuren DP, et al. Open discussion of negative emissions is urgently needed. Nat Energy 2017a;2:902–4.
[19] Creutzig F, et al. Towards demand-side solutions for mitigating climate change. Nat Clim Change 2018;8:268–71.
[20] Grubler A, et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat Energy 2018;3:515–27.
[21] Hof AF, et al. From global to national scenarios: bridging different models to explore power generation decarbonisation based on insights from socio-technical transition case studies. Technol Forecast Soc Change 2020;151.
[22] van Sluisveld MAE, et al. Exploring the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. Technol Forecast Soc Change 2016;102:309–19.

[23] Van Vuuren DP, et al. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. Nat Clim Change 2018;8:391–7.
[24] Bogdanov D, et al. Full energy sector transition towards 100% renewable energy supply: integrating power, heat, transport and industry sectors including desalination. Appl Energy 2021;283.
[25] Connolly D, et al. Smart Energy Europe: the technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60:1634–53.
[26] Doepfert M, Castro R. Techno-economic optimization of a 100% renewable energy system in 2050 for countries with high shares of hydropower: the case of Portugal. Renew Energy 2021;165:491–503.
[27] Jacobson MZ, et al. 100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world. Joule 2017;1:108–21.
[28] Jacobson MZ, et al. 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. Energy Environ Sci 2015;8:2093–117.
[29] Lu B, et al. A zero-carbon, reliable and affordable energy future in Australia. Energy 2021;220.
[30] Stehfest E, et al. Integrated assessment of global environmental change with IMAGE 3.0. Model description and policy applications. The Hague. The Netherlands: PBL Netherlands Environmental Assessment Agency; 2014.
[31] Esmeijer K, et al. 2 °C and 1.5 °C scenarios and possibilities of limiting the use of BECCS and bio-energy. The Hague: PBL Netherlands Environmental Assessment Agency; 2018.
[32] van Vuuren DP. Energy systems and climate policy - long-term scenarios for an uncertain future. Copernicus Institute of Sustainable Development. Utrecht University; 2007.
[33] Van Vuuren DP, et al. Limiting global temperature change to 1.5 °C. Implications for carbon budgets, emission pathways, and energy transitions. The Hague: PBL Netherlands Environmental Assessment Agency; 2017.
[34] Rogner H. Energy resources and potentials. Glob Energy Assess Toward Sustain Future 2012:423–512.
[35] Meinshausen M, et al. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 1: model description and calibration. Atmos Chem Phys 2011;11:1417–56.
[36] Van Vuuren DP, et al. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environ Change 2017b;42:237–50.
[37] Hof AF, et al. The effect of updated pledges and business-as-usual projections, and new agreed rules on expected global greenhouse gas emissions in 2020. Environ Sci Pol 2013;33:308–19.
[38] Willett MDWC. Eat, drink, and Be healthy: the harvard medical school guide to healthy eating. Free Press; 2005.
[39] Bijl DL, et al. A physically-based model of long-term food demand. Global Environ Change 2017;45:47–62.
[40] Luderer G, et al. Assessment of wind and solar power in global low-carbon energy scenarios: an introduction. Energy Econ 2017;64:542–51.
[41] Ang BW, et al. Energy security: definitions, dimensions and indexes. Renew Sustain Energy Rev 2015;42:1077–93.
[42] Asia Pacific Energy Research Centre. A quest for energy security in the 21st century. Japan: Institute of energy economics; 2007.
[43] Daioglou V, et al. Implications of climate change mitigation scenarios on international bioenergy trade. Climatic Change. 2020 (in press).
[44] Doelman JC, et al. Exploring SSP land-use dynamics using the IMAGE model: regional and gridded scenarios of land-use change and land-based climate change mitigation. Global Environ Change 2018;48:119–35.
[45] Bauer N, et al. Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. Climatic Change 2018.
[46] Daioglou V, et al. Integrated assessment of biomass supply and demand in climate change mitigation scenarios. Global Environ Change 2019;54:88–101.
[47] Daioglou V, et al. Projections of the availability and cost of residues from agriculture and forestry, vol. 8; 2016. p. 456–70.
[48] Huppmann D, et al. IAMC 1.5°C scenario explorer and data hosted by IIASA. Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis; 2018.
[49] Koelbl BS, et al. Uncertainty in the deployment of Carbon Capture and Storage (CCS): a sensitivity analysis to techno-economic parameter uncertainty. Int J Greenh Gas Contr 2014;27:81–102.
[50] Krey V, et al. Getting from here to there – energy technology transformation pathways in the EMF27 scenarios. Climatic Change 2014;123:369–82.
[51] IEA. World energy outlook 2019. International Energy Agency; 2019.
[52] Capellán-Pérez I, et al. Likelihood of climate change pathways under uncertainty on fossil fuel resource availability. Energy Environ Sci 2016;9:2482–96.
[53] Wang J, et al. The implications of fossil fuel supply constraints on climate change projections: a supply-side analysis. Futures 2017;86:58–72.
[54] Kharecha PA, Hansen JE. Implications of "peak oil" for atmospheric CO2 and climate. Global Biogeochem Cycles 2008;22.
[55] European Commission. Impact Assessment Accompanying the Document Stepping up Europe's 2030 climate ambition: investing in a climate-neutral future for the benefit of our people. 2020. Part2/2, https://ec.europa.eu/transparency/regdoc/rep/10102/2020/EN/SWD-2020-176-F1-EN-MAIN-PART-2.PDF.