Research Article

Global sector-specific *Scope 1*, *2*, and *3* analyses for setting net-zero targets: agriculture, forestry, and processing harvested products

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Abstract
The aim of this research was the development of global 1.5 °C net-zero pathways for specific industries as classified under the Global Industry Classification System (GICS). In this article, we described the analysis of the *Agriculture & Food* and *Forestry & Wood Products* categories to determine their industry-specific Scope *1*, *2*, and *3* emissions on a global level. The accounting methodologies for *Scope 3* emissions were developed for entity-level accounting and reporting. However, we suggested an alteration of the methodology for industry-wide *Scope 3* analyses because of poor data availability and to avoid counting emissions twice. In this article, we described the calculation method and the key results for net-zero pathways for these two industry sectors. We showed that the decarbonization of the energy supply is possible for both sectors globally by 2050. We also described the land-use-related *Scope 3* emissions for the agriculture and forestry sectors. The agricultural sector is unlikely to reach net-zero emissions by 2050, whereas the forest industry can become carbon negative.

Article Highlights

- Scope 1, 2 and 3 calculation methodology for whole industry sectors that avoids double counting.
- Net-Zero decarbonization pathways for agriculture, forestry, and processing harvested products.
- Role of naturebased systems for negative emissions and the lack of implementation mechanisms.

Keywords 1.5 °C Pathways · Scope 1, 2, 3 · Industry sectors · Decarbonization · Agriculture industry · Food processing industry · Forestry, wood products industry

1 Introduction

This article summarizes the results of a research project undertaken between October 2020 and May 2022 at the University of Technology Sydney (UTS) to develop industry sector specific decarbonization pathways. The aim of this project was to develop verifiable key performance indicators in relation to energy intensity and emissions intensity of clearly defined industrial sectors for financial institutions, which can be used as benchmarks for financial

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products. This article builds on two scientific articles published in April 2022; the methodology description of the One Earth Climate Model, an integrated energy assessment model [1] and the documentation of the development of energy scenarios for industry sectors classified under the Global Industry Classification Standard (GICS) [2]. Furthermore, a project report published in May 2022 during a webinar hosted by the United Nations Program Responsible Investment UN PRI is cited [3]. The significance and novelty of this paper is that it brings together the separate parts of the research and explains in detail the development of a new methodology for calculating Scope 1, 2 and 3 emissions using the example of two industry sectors—agriculture and forestry—and draws conclusions for the entire research project.

The Intergovernmental Panel on Climate Change (IPCC) released the Sixth Assessment Report (AR6) of Working Group I in August 2021, which focuses on the physical science basis of climate change [4]. One of the key headline statements for policy makers is that '*from a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions. Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality*'[5].

The United Nations states that setting net-zero targets is a critical longer-term goal in ensuring steep emissions cuts, and reports that '*along with companies, cities and financial institutions, more than 130 countries have now set or are considering a target of reducing emissions to net zero by mid-century*' [6, 7]. Setting net-zero targets requires a scientific basis, and research in this area has increased significantly in recent years. The International Energy Agency has published 'Net Zero by 2050—A Roadmap for the Global Energy Sector' [8] to support the establishment of net-zero targets. However, the International Energy Agency (IEA) does not provide disaggregated information on the *Scope 1*, *2*, and *3* emissions for industry sectors, which is required for target setting, especially for institutional investors.

The UN-convened Net-Zero Asset Owner Alliance (NZAOA) is an international group of institutional investors committed to transitioning their investment portfolios to net-zero emissions by 2050 [9]. The Institute for Sustainable Futures, University of Technology Sydney (UTS/ISF), has been commissioned by NZAOA to develop science-based sectorial decarbonization pathways and targets (energy and greenhouse gas [GHG] emissions trajectories), broken down into *Scopes 1*, *2*, and *3*, for industry sectors classified under the Global Industry Categorisation Standard (GICS) [10]. The project includes various industry sectors, but in this article, we focus on agriculture, forestry, and their end products. Implication of this research for investors is to improve comparability of Scope 1, 2 and 3 targets among the finance industry via improved definition standards for each of the three scopes for each industry.

The OneEarth Climate Model (OECM) is an integrated assessment model for climate and energy pathways, which focuses on 1.5 °C scenarios [11]. The OECM net-zero pathways are developed on the basis of a total global carbon budget of 400 $GtCO_2$ between 2020 and 2050, to achieve a maximum global temperature rise of 1.5 °C with 67% likelihood, as defined in IPCC AR6 (2021). In this research, the OECM has been developed further to address the requirements of sectorial pathways. To develop energy scenarios for GICS-classified industry sectors, significant improvement in the technological resolution of OECM was required. The demand and supply calculations also had to be broken down into industry sectors to develop individual pathways.

The foci of this article are two very complex industry sectors: agriculture, from food production to processing, and forestry, from harvesting to wood products. Unlike most sectors, the majority of GHG emissions from agriculture and forestry are related to land use. By comparison, the emissions from energy use are relatively small for these sectors, contributing about 2% of total global energy-related CO_2 emissions. This study also includes an explanation of the OECM *Scope 1*, *2*, and *3* calculation methodologies for GICS-based industries and geographic areas (countries, regions, and/or globally).

In the next two sections, we present an overview of the OneEarth Climate Model and the methodologies for Scopes 1, 2, and 3 emissions respectively, Sect. 4 shows an overview of the global agriculture and food sector and the global forestry sector. It includes the energy and land use demands of the sectors and a discussion on meeting global food demand while reducing the environmental impact of food production. In Sect. 5, we consider the energy supply and emissions results from the analysis and Sect. 6 presents the conclusion.

2 OneEarth climate model 2.0—methodology

The One Earth Climate Model (OECM 1.0) emerged from an interdisciplinary research project between the University of Technology Sydney, the German Aerospace Centre, and the University of Melbourne between 2017 and 2019. The task was to develop a detailed 1.5 °C GHG trajectory for 10 world regions. OECM 1.0 was developed on the basis of established energy models and consisted of three independent modules:

1. Energy system model (EM): a mathematical accounting system for the energy sector [12];
2. Transport scenario model TRAEM (TRAnsport Energy Model) with high technical resolution [13];
3. Power system analysis model [R]E 24/7, which simulates the electricity system on an hourly basis and at geographic resolution to assess the infrastructure requirements, such as grid connections, between different regions and electricity storage types, depending on the demand profiles and power-generation characteristics of the system [14].

The advanced OneEarth Climate Model (OECM 2.0) merges the energy system model EM, the transport model TRAEM, and the power system model [R]E 24/7 into one MATLAB-based energy system module. The GICS was used to define the sectors of the economy. The global finance industry must increasingly undertake mandatory Climate Change Stress Tests for GICS-classified industry sectors in order to develop energy and emissions benchmarks to implement the Paris Agreement. This will require very high technical resolution for the calculation and projection of future energy demands and the supply of electricity, (process) heat, and fuels that are necessary for the steel and chemical industries. An energy model with high technical resolution must be able to calculate energy demands based on either projections of the sector-specific gross domestic product (GDP) or market forecasts of material flows, such as the demand for steel, aluminium, or cement in tonnes per year.

The main improvements in the OECM 1.0 methodology documented, by [15], are:

1. Merger of three independent models into one interconnected model;
2. Significantly increased technical resolution for all sectors;
3. Industry-sector-specific energy demand and supply scenarios;
4. Inclusion of sector-specific process and land-use emissions.

The OECM 2.0 program is modular and currently includes 12 different industry sectors. An expansion to more sectors or sub-sectors is possible without great effort. The OECM 2.0 tier 1 inputs are population and GDP by region and industry sector as main drivers of the energy demand. Tier 2 demand parameters are energy-relevant factors, and describe technical applications, their energy intensities, and the extent to which the application is used. The OECM 2.0 input and out parameter as well as the used codes and equations are documented in great detail in [1].

The OECM is an integrated energy assessment model that covers the entire global energy system, broken down into various sub-sectors. In this paper, we focus on the 'agriculture and food processing' and 'forestry and wood products' sector However, the projections for the economic development for these sectors are developed in the context of the overall global socio-economic development—namely, the development of the population and the projected GDP until 2050. Furthermore, those sector-specific projections are based on the results of workshops with industry, academia, and the NZAOA Scientific Advisory Board organized by the Net-Zero Asset Owner Alliance (NZAOA) between May 2020 and November 2021.

3 Methodologies for identifying and reporting *Scopes 1*, *2*, and *3 emissions*

Reporting corporate GHG emissions is important, and the focus is no longer on direct energy-related CO_2 emissions but includes other GHGs emitted by industries. This section contains materials published in May 2022 by the authors of this article [3].

These increasingly include the indirect emissions that occur in supply chains [16]. The Greenhouse Gas Protocol, a global corporate GHG accounting and reporting standard [17], distinguishes between three 'scopes':

- *Scope 1*—emissions are direct emissions from owned or controlled sources;
- *Scope 2*—emissions are indirect emissions from the generation of purchased energy;
- *Scope 3*—emissions are all the indirect emissions (not included in *Scope 2*) that occur in the value chain of the reporting company, including both upstream and downstream emissions.

The United States Environmental Protection Agency (US EPA) defines *Scope 3* emissions as 'the result of activities from assets not owned or controlled by the reporting organization, but that the organization indirectly impacts in its value chain. They include upstream and downstream of the organization's activities' [18]. According to the US EPA, *Scope 3* emissions include all sources of emissions not within an organization's *Scope 1* and *2* boundaries, and the *Scope 3* emissions of one organization are the *Scope 1* and *2* emissions of another organization. *Scope 3* emissions, also referred to as 'value chain emissions' or indirect emissions, often represent the majority of an organization's total GHG emissions [18].

Table 1 Upstream and downstream *Scope 3* emissions categories [10, 22]

Upstream		Downstream	
Greenhouse Gas Protocol Scope 3	OECM 2.0—emissions included in the following sectors	Greenhouse Gas Protocol Scope 3	OECM 2.0—emissions included in the following sectors
U1 Business travel	Part of the respective transport mode (aviation, road, rail, etc.)	D1 Use of solid products	All sector uses of solid products are included
U2 Purchased goods and services	All sector-specific goods and services are included	D2 Downstream transportation and distribution	Sector-specific transportation and distribution and end-of-life treatment are included. This includes the actual use of the product, e.g., emissions when driving a manufactured car
U3 Waste generated in operations	All waste generated in sector-specific operations are included	D3 End-of-life treatment of solid products	
U4 Fuel- and energy-related activities	All sector fuel- and energy-related activities are included	D4 Investments	Not included
U5 Employee commuting	Part of the respective transport mode (aviation, road, rail, etc.)	D5 Downstream leased assets	Not included
U6 Upstream transportation and distribution	Part of the respective transport mode (aviation, road, rail, etc.)	D6 Processing of solid products	All sector processing of solid products is included
U7 Capital goods	Not included	D7 Franchises	Not included
U8 Upstream-leased assets	Not included		

Whereas the methodologies of *Scope 1* and *Scope 2* are undisputed, the method of calculating *Scope 3* emissions is an area of ongoing discussion and development [19–21]. The main issues discussed are data availability, reporting challenges, and the risk of double counting. MSCI, for example, avoids double counting by using a 'de-duplication multiplier of approximately 0.205' [10]. This implies that the allocation of emissions based on actual data is not possible. Accounting methodologies for *Scope 3* emissions have been developed for entity-level accounting and reporting [22].

Ducoulombier (2021) found that the reporting of *Scope 3* emissions ('indirect emissions') is incomplete and that reporting standards to support the comparison of companies are missing [23]. Schulman et al. (2021) found that over 80% of emissions in the food industry are *Scope 3* emissions, and that the data reported by the Customer Data Platform (CDP), a global data service for investors, companies, cities, states and regions, are incomplete and inconsistent throughout [24].

In 2009, Huang et al. suggested that 'Protocol organizations should actively make more specific *Scope 3* guidelines available for their constituents by developing sector-specific categorizations for as many sectors as they feasibly can and create broader industry-specific protocols for others'. Therefore, the accounting methodology for *Scope 3* emissions requires significant improvement and has been under discussion for more than a decade.

The OECM model focuses on the development of 1.5 °C net-zero pathways for industry sectors classified under the GICS [10], for countries or regions or at the global level. Emissions methodologies for entity-level *Scope 3* require bottom-up entity-level data to arrive at exact figures. Thus, data availability and accounting systems for whole industry sectors on a regional or global level present significant challenges.

Therefore, the *Scope 3* calculation methodology had to be simplified for country-, regional-, and global-level calculations and to avoid double counting. In the Greenhouse Gas Protocol, *Scope 3* emissions are categorised into 15 categories, shown in Table 1.

To include all the upstream and downstream categories shown in Table 1 for an entire industry sector is not possible because firstly, complete data are not available—for example, how many kilometres employees for the agricultural or forestry sector commute —and secondly, it is impossible to avoid double counting—for example, when calculating Scope 3 for the car industry. Both the emissions for manufacturing and using a passenger vehicle are emissions for road transport as shown in Fig. 1. Table 1 identifies how the 15 categories are handled in the proposed OECM 2.0 methodology.

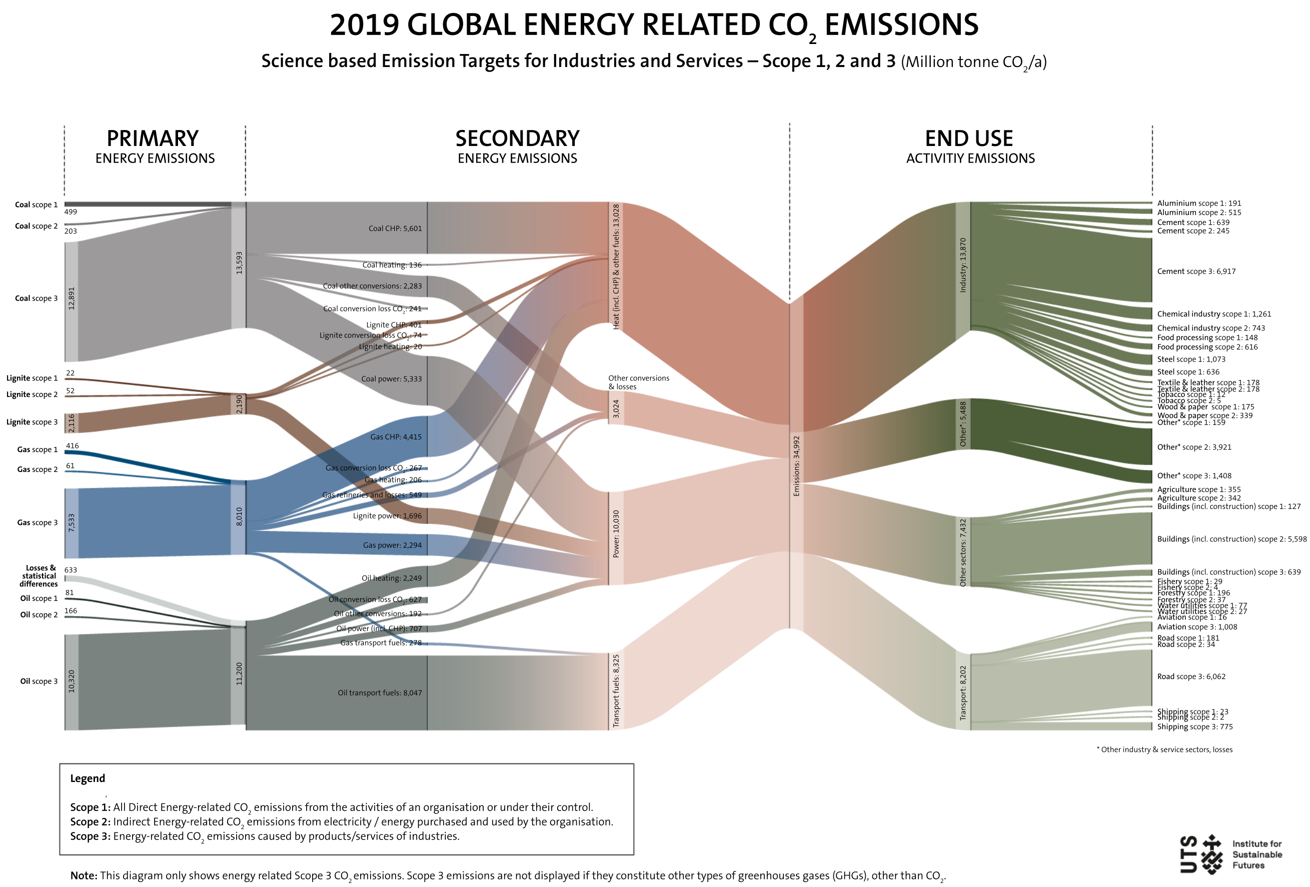

Fig. 1 Energy-related Scope 1, 2, and 3 CO_2 emissions for the primary and secondary energy industries and for the end-use sector in 2019

The OECM methodology is based on the *Technical Guidance for Calculating Scope 3 Emissions* of the World Resource Institute [22], but is simplified to reflect the higher level of industry- and country-specific pathways. The OECM defines the three emissions scopes as follows:

Scope 1—All direct emissions from the activities of an organisation or under their control, including fuel combustion on site (such as gas boilers), fleet vehicles, and air-conditioning leaks.

Limitations of the OECM *Scope 1* analysis: Only economic activities covered under the sector-specific GICS classification and are counted for the sector are included. All energy demands reported by the IEA *Advanced World Energy Balances* [25] for the specific sector are included.

Scope 2—Indirect emissions from electricity purchased and used by the organisation. Emissions are created during the production of energy and are eventually used by the organisation.

Limitations of the OECM *Scope 2* analysis: Due to poor data availability, the calculation of emissions focuses on the electricity demand and 'own consumption', e.g., that reported for power generation by [26].

Scope 3—GHG emissions caused by the analysed industry that are limited to sector-specific activities and/or products classified in GICS.

Limitations of the OECM *Scope 3* analysis: Only sector-specific emissions are included. Traveling, commuting, and all other transport-related emissions are reported under *'transport'*. The lease of buildings is reported under '*buildings*'. All other financial activities, such as '*capital goods*', are excluded because no data are available for the GICS industry sectors and would lead to double counting. The OECM is limited to energy-related carbon dioxide (CO_2) and energy-related methane (CH_4) emissions. All other GHG gases are calculated outside the OECM model by [27].

The main difference from the World Resources Institute (WRI) concept is that the interactions between industries

Table 2 Schematic representation of OECM *Scopes 1*, *2*, and *3* according to GICS classes to avoid double counting

	Primary class					Secondary class				End-use activity class			
	GICS 10 Energy	Scope 1	Scope 2	Scope 3		GICS 55 Utilities	Scope 1	Scope 2	Scope 3	All other Industries and Services	Scope 1	Scope 2	Scope 3
CO_2					CO_2								
CH_2 AFOLU					CH_2 AFOLU								
CH_4					CH_4								
N_2O					N_2O								
					CFCs								
Total GHG	Sum of *Scopes 1*, *2*, and *3* equals total emissions				Total GHG	Sum of *Scopes 1*, *2*, and *3* equals total emissions				Sum of *Scopes 1*, *2*, and *3* equals total emissions			

and/or other services are kept separate. The OECM reports only emissions directly related to the economic activities classified by GICS. Furthermore, the industries are broken down into three categories: Primary Class, Secondary Class, and End-use Activity Class.

Table 2 shows a schematic representation of the OECM *Scope 1*, *2*, and *3* calculation method according to GICS class, used to avoid double counting. The sum of *Scopes 1*, *2*, and *3* for each of the three categories is equal to the actual emissions. Example: Total annual global energy-related CO_2 emissions are 35 Gt in a given year.

- The sum of *Scope 1*, *2*, and *3* for the primary class (primary energy industry) is 35 Gt CO_2
- The sum of Scope 1, 2, and 3 for the secondary class (secondary energy industry/utilities) is 35 Gt CO_2
- The sum of Scope 1, 2, and 3 for end-use activities (all end-use sectors) is 35 Gt CO_2

Double counting can be avoided by defining a primary class for the primary energy industry, a secondary class for the supply utilities, and an end-use class for all the economic activities that use the energy from the primary- and secondary-class companies. Furthermore, the separation of all emissions by defined industry categories—such as GICS—streamlines the accounting and reporting systems. The volume of data required is reduced and reporting is considerably simplified under the OECM methodology as document in [28].

Achieving the global target of 1.5 °C and net-zero emissions by 2050 under the Paris Agreement for a specific industry sector, requires all its business activities with other sectors to also commit to a 1.5 °C–net-zero emissions targets.

3.1 Reporting Scope 1, 2 and 3 emission: a sankey diagram for energy-related CO_2 emissions

Figure 1 shows the energy-related CO_2 emissions for 12 industry sectors in 2019 as a specific example for the *Scope 1*, *2* and *3* reporting methodology developed for this analysis. The CO_2 emissions of the primary energy industry are on the left, the emissions from the secondary energy industry—energy utilities that provide energy services for end-users—are in middle. The energy-related CO_2 emissions from end-use sectors are on the right. As presented in Sect. 3, *Scope 1* emissions include all activities of the specific industry or service sector which or under their direct control. An example for the primary energy sector is the energy demand for oil extraction and to refine it to gasoline for cars. Scope 2 emissions for the primary energy sector are those from purchased energy services such as electricity for the oil refinery. Finally Scope 3 emissions are

Table 3 Relevant Global Industry Classification Standard (GICS) sectors

Sector	Industry group	Industry	Sub- industry	Description
Consumer Staples 30	Food, Beverages and Tobacco 3020	Food Products 302020	Agricultural Products 30202010	Producers of agricultural products. Includes crop growers, owners of plantations and companies that produce and process foods but do not package or market them. Excludes companies classified in the Forest Products Sub-industry and those that package and market the food products classified in the Packaged Foods Sub-industry
			Packaged Foods and Meats 30202030	Producers of packaged foods, including dairy products, fruit juices, meats, poultry, fish, and pet foods
		Tobacco 302030	Tobacco 30203010	Manufacturers of cigarettes and other tobacco products
Materials 15	Materials 1510	Paper and Forest Products 151050	Forest Products 15105010	Manufactures timber and related wood products. Includes lumber for the building industry
			Paper Products 15105020	Manufactures all grades of paper. Excludes companies specializing in paper packaging, which is classified in the Paper Packaging Sub-Industry

those caused by the product and/or service provided by the sector. For the oil industry, Scope 3 emissions include those caused by gasoline use for cars. The majority of energy related CO_2 emissions are caused by industry and transport sector as well as in buildings—mainly for climatization (heating and cooling). Both the agriculture sector—from food production to processing—and the forestry sector—from harvesting to wood products—generate major GHG emissions from land-use changes respective the use of the soil. However, unlike most industry and service sectors, the climate-relevant CO_2 emissions from energy use are relatively small for these sectors, contributing about 2% of the total global energy-related CO_2 emissions.

3.1.1 Non-energy-related emissions from agriculture and forestry

The impacts of agriculture, forestry, and other land uses (AFOLU) can be both positive and negative. The IPCC describes AFOLU emissions as follows: '*Plants take up carbon dioxide (CO_2) from the atmosphere and nitrogen (N) from the soil when they grow, re-distributing it among different pools, including above and below-ground living biomass, dead residues, and soil organic matter. The CO_2 and other non-CO_2 greenhouse gases (GHG), largely methane (CH_4) and nitrous oxide (N_2O), are in turn released to the atmosphere by plant respiration, by decomposition of dead plant biomass and soil organic matter, and by combustion*' [29].

4 Overview of the global agriculture and food sector

The following section gives a brief overview of the global *agriculture and food* sector in terms of the key economic parameters, and details of its GICS classification.

Economic significance: The agriculture and food sector is an essential economic sector contributing to food security, livelihoods, and well-being. Valued at 3.5 trillion USD, agriculture, forestry, and fisheries (AFF)[1] accounted for 4% of global GDP in 2019, with the largest contributions from China and India. The value added[2] in agriculture[3] alone was 0.2 trillion USD [30, 31]. Value is also added in some of the manufacturing sectors supported by AFF. In 2018, the manufacture of food and beverages contributed 1.5 trillion USD and the manufacture of tobacco products contributed 167 billion USD [32].

Global Industry Classification Standard: The corresponding GICS sectors addressed in this report are listed in Table 3 [33].

[1] Corresponds to ISIC divisions 1–3 and includes forestry, hunting, and fishing, as well as cultivation of crops and livestock production.

[2] Net output of a sector after all the outputs are summed and the intermediate inputs subtracted.

[3] Includes crop and animal production, hunting, and related service activities (ISIC division A_01).

Table 4 Input—Economic development—agriculture and food processing: 2019 and projections towards 2050. *Source*: Food and Agriculture Organisation of the United Nations (FAOSTAT: Production)

Parameter	Unit	2019	2025	2030	2035	2040	2050
			Input assumptions				
Global GDP	[bn $]	129,555	142,592	196,715	231,758	266,801	346,236
Agriculture—economic value	[bn $]	3887	4687	5533	6518	7504	9738
Food and processing industry	[bn $]	1010	1326	1565	1844	2123	2755
Global GDP share	[%]	3.8%	4.2%	3.6%	3.6%	3.6%	3.6%
Total volume—main food products	[million tonnes]	9609	10,068	10,392	10,689	10,953	11,415
Cereals, total	[million tonnes]	2979	3159	3285	3400	3502	3680
Pulses, total	[million tonnes]	88	94	97	101	104	109
Vegetables, primary	[million tonnes]	1130	1199	1246	1290	1329	1396
Roots and tubers, total	[million tonnes]	861	913	950	983	1012	1064
Sugar crops, primary	[million tonnes]	2229	2242	2253	2265	2276	2299
Oil crops	[million tonnes]	1101	1168	1215	1257	1295	1360
Milk, total	[million tonnes]	883	937	974	1008	1039	1091
Meat, total	[million tonnes]	337	357	371	384	396	416

Main products: The most widely produced commodities in the world are cereals, sugar crops, vegetables, and oil crops. The area under agricultural use has been increasing since the 1960s, until it started to plateau at the beginning of this century, with almost 5 billion hectares under cultivation by 2018. China, the United States, and Australia have the largest areas of agricultural land [31]. Besides land and energy (discussed in the next section), the other major inputs to agriculture are fertilizers and pesticides, which have been increasing progressively over time.

4.1 Energy demand of the global agriculture and food sector

Although energy is an important input to agriculture, the sector accounts for only 2.2% of the total final energy consumption globally, with oil and oil products meeting most of this demand [34]. Generally, as agriculture is industrialised, this energy consumption increases. In regions where most agricultural systems are industrialised, efficiency gains may have plateaued (in USA, after a peak in 2006 [31]) or the sectoral final energy consumption may even have decreased (in EU, 10.8% decrease since 1998 [35]).

However, together with the global food systems, the sector is estimated to account for almost one third of the world's total final energy demand. In high-GDP countries, approximately 25% of the total sectoral energy is consumed behind the farm-gate (including in fisheries): 45% in food processing and distribution, and 30% in retail, preparation, and cooking [36]. In low-GDP countries, a smaller share is spent on the farm and a greater share on cooking [37].

In this study, projections of the future energy demand for the agriculture and food-processing sector are based on GDP development projections. The assumed global GDP projections until 2050 are based on World Bank and IEA projections [38]. It is anticipated that both the agriculture and food and processing industries will grow in proportion to the global economy and that their share of the global GDP will remain between 3.5 and 4%. The production volumes for cereals, pulses, and other agricultural products for 2019, shown in Table 4, are taken from the Food and Agriculture Organization (FAO) database [31]. The estimated global population growth is based on UN population projections [39], and will decrease evenly from about 1% per year in 2020 to 0.5% per year in 2050. The food production volumes for each product shown will develop accordingly. Thus, no dietary changes are assumed in estimating the future energy demand of the agriculture and food-processing sector. However, the impacts of dietary changes are discussed in the next section.

According to the IEA's *Advanced Energy Balances* database structure, the food-processing industry is part of the *Industry* sector, whereas agriculture is part of the *Other sectors* group. Furthermore, the statistical data for the relevant energy demand are provided as 'food and tobacco', and separate data for the food processing industry are not available. Similarly, the IEA database provides the energy demand for agriculture and forestry, but no further separation of the two industries is available. To calculate the energy demand for each sub-sector, the economic values in $GDP energy for agriculture, forestry, food processing, and the tobacco industry, are divided by the average energy intensities (in MJ per $GDP) for each of those

Table 5 Input—Energy intensities for selected food-processing industries

Energy intensities		2019	2025	2030	2035	2040	2050
			Input assumptions				
Bakery products industry	[MJ/$GDP]	3.32	3.28	3.24	3.20	3.16	3.08
Assumed efficiency increase per year	[%/year]		0.25%	0.25%	0.25%	0.25%	0.25%
Fruit and vegetable industries	[MJ/$GDP]	7.26	7.17	7.08	6.99	6.90	6.73
Assumed efficiency increase per year	[%/year]		0.25%	0.25%	0.25%	0.25%	0.25%
Dairy products industry	[MJ/$GDP]	4.02	3.97	3.92	3.87	3.82	3.73
Assumed efficiency increase per year	[%/year]		0.25%	0.25%	0.25%	0.25%	0.25%
Meat products industries	[MJ/$GDP]	3.49	3.45	3.40	3.36	3.32	3.24
Assumed efficiency increase per year	[%/year]		0.25%	0.25%	0.25%	0.25%	0.25%
Average food-processing industry	[MJ/$GDP]	3.49	2.82	2.81	2.8	2.78	2.67
Assumed efficiency increase per year	[%/year]		1%	0.1%	0.1%	0.1%	0.1%
Average agriculture and farming	[MJ/$GDP]	1.74	1.53	1.39	1.27	1.15	0.96
Assumed efficiency increase per year	[%/year]		1%	0.8%	0.8%	0.8%	0.8%

Table 6 Results -energy demand for agriculture and food processing

Parameter	Unit	2019	2025	2030	2035	2040	2050
			Calculated results				
Agriculture: total energy demand	[PJ/year]	7803	8655	9297	9967	10,442	11,221
Agriculture: heat and fuels	[PJ/year]	5421	6058	6508	6977	7309	7855
Agriculture: electricity demand	[PJ/year]	2450	2873	3087	3309	3467	3725
	[TWh/year]	681	798	857	919	963	1035
Food processing: total energy demand	[PJ/year]	6071	6381	7498	8795	4117	12,549
Food processing: electricity demand	[PJ/year]	1931	2000	2349	2755	3156	3932
	[TWh/year]	536	556	653	765	877	1092
Food processing: heat and fuels	[PJ/year]	4117	4338	5099	5982	6857	8533

sectors. Table 5 shows a selection of energy intensities taken from the IEA database for different agricultural products. To calibrate the model and to understand the development in the past, statistical data for the years 2005–2019 are used. To project the future energy demand for each of the sub-sectors, the calculation method then changes and the projected GDP development (Table 4) is multiplied by the average sector-specific energy intensities, incorporating an assumed efficiency factor—the assumed increase of efficiency in percent per year—giving the projected energy demand. For more details of the OECM methodology, see [11].

The average energy intensity of the food-processing industry for 2019 has been calculated to be around 3.5 MJ/GDP, and it is assumed that the annual efficiency gain is 0.25% on average (Table 5). The main energy demand for food processing is for heating processes in the range of 100–500 °C. Based on [40] the share of thermal energy is estimated to be 75% of final energy demand on average for food processing and the remaining 25% for electricity. Transport energy is not included in this approach because the transport sector is analysed separately (see the Methodologies for *Scopes 1*, *2*, and *3* section).

Based on the methodology described above, the energy demand for the agriculture and farming sector is calculated as an energy intensity of 1.74 MJ per $GDP for the base year 2019. The majority of the energy demand is estimated to be for fuel for agricultural machinery, such as tractors and harvesters, whereas 30% of the energy is electricity. Efficiency gains for the agriculture sector are assumed to be higher—0.8 to 1% per year—than for the food-processing industry due to replacement of fuels for tractors and other working machinery with electric drives. According to IEA energy statistics, around 75% of the energy consumed for food processing is related to process heat and other thermal usages including cooling. It is assumed that the replacement of combustion engine powered tractors and work machinery and the increased utilization of efficient water pumps used for the agricultural sector can be introduced faster than the optimization of manufacturing processes in the food industry.

Table 6 shows the calculated energy demand broken down according to the electricity, heat, and fuel requirements for the agriculture and food-processing sector. The global average shares of fossil-fuel-derived and renewable heat supplies are also provided (Tables 12 and 13). The supply scenarios for heating, electricity, and other fuels are based on [15]and were updated in this project.

4.1.1 Food demand and implications

4.1.1.1 Food equity The FAO estimates that sufficient global aggregate food is produced for nearly everyone to be well fed. However, income inequalities and resource constraints in different parts of the world mean that everyone is not well fed. Progress towards eliminating hunger and malnutrition is still lagging, with 768 million people undernourished in 2020 [41]. However, while we recognise the need for the redistribution of available food calories and a discussion of nutrition, in this research we take a global aggregate view of food production, rather than a nuanced view of food security and nutritional equity in the local context.

4.1.1.2 Demand for agricultural products and food The global demand for food for human consumption is the main component of the overall demand for agricultural products. The key drivers of food (and consequently feed) demand are population growth and changes in consumption patterns, which are driving a shift to a more meat-based diet. Income, individual preferences and changes in lifestyle and consumption patterns will play a greater role in the demand for vegetable oils, sugar, meat, and dairy products [42]. The demand for commodities, such as food grains, is primarily driven by increases in population as "per capita food demand is stagnant or even decreasing in several high-income countries (although the demand for coarse grains for use as feed will increase as meat and dairy consumption increases) [42]. As livestock production expands to meet this increase in meat and dairy consumption. The use of cereals for feed is projected to grow at 1.2% per year till 2030 particularly in low- and middle-income countries [43].

Non-food uses of several commodities, mainly animal feed and fuel, are important and have experienced faster growth than food for human consumption in the recent years. Looking forward to 2030, it is anticipated that the "relative importance of food, feed, and biofuel use will remain constant, because no major structural shifts in the demand for agricultural commodities are expected" [42]. However, there is a projected slowdown for overall global demand of agricultural commodities (1.2% projected growth per year over the coming decade, as compared to the 2.2% per year growth over the last decade) due to a lower global demand for biofuels, especially as many high-income and emerging countries achieve saturation levels [43].

Based on the 2012 FAO projection, the overall production for agricultural products is expected to be 60% higher by 2050 as compared to 2005/2007 to meet the increased demand and may necessitate about 70 million ha of additional land for agricultural use in 2050 [45]. Several studies have discussed doubling production to meet the 2050 demand, particularly given the shift toward protein-rich diets and the consequent need for land to grow animal feed [46]. It was noted that "scenarios that do not link production with health and nutrition involve the expansion of agricultural lands into forests" [47]. Hunter et al., (2017) however, disagree with the estimates for doubling agriculture production, largely because of recent production gains, and claim that "an increase of approximately 25–70% above the current production levels may be sufficient to meet the 2050 demand" [48], 49 noted that the planetary boundary for agricultural land was already exceeded in 2010, and a 2050 scenario without efficiency gains to meet the increased demand for food would require an increase of > 3.5 Gha in agricultural land (grassland and cropland areas would increase by 78% and 67%, respectively). The FAO's latest alternative pathways to 2050 estimate that arable land must increase by 86 million hectares from 2012 in the sustainability scenario and by 165 million hectares in the business-as-usual scenario [50].

4.1.1.3 Mapping land use for food As seen in the previous section, projections of the increased land required for agriculture range from 70 million ha to 3.5 billion ha. The very large range between the two areas is due to very different assumptions: The lower estimate (70 million ha) refers to a future food system that is significantly more efficient than when the study was published in 2012 [45]; and if no efficiency measures would be implemented, food production would require 3.5 billion ha in 2050 [49]. This shows the importance of yield efficiencies in food production.

FAO has identified a global reserve of at least 400 million ha of suitable and unprotected land that could be brought under rain-fed cultivation. However, under a business-as-usual scenario the losses to urbanization and degradation could result in less than half of this reserve being available [50]. Data from the FAO–International Institute for Applied Systems Analysis (IIASA) Global Agro-Ecological Zones (GAEZ v4) suggest that "around 360 million ha of additional, unprotected, and highly suitable areas for rain-fed crop production will be available by 2050". Therefore, if expansion is coupled to the other strategies listed above, there may be enough land to feed the 9 billion people estimated in 2050. The majority of this land is situated in low- and medium-income countries [50].

All these scenarios involve increasing agricultural land at the expense of forests, and the resulting deforestation will have drastic consequences for the emissions intensity of the sector.

4.1.2 Meeting global food demand while reducing the environmental impact of food production

As noted above, a major source of emissions from the agricultural sector is associated with land use. Key complementary strategies for increasing food production while reducing the impact on land use are discussed below, followed by a discussion of the environmental impacts and emissions specifically related to animal protein production, including enteric emissions. These impacts are fundamentally driven by the overall demand for agricultural products.

4.1.2.1 Crop yield Yield increases, rather than major expansion of cropland will provide the increased demand for food in the future. The FAO estimates 80% of this increased production to come from yield increases, compared with 10% from the expansion of arable land and 10% from increases in cropping intensities [45]. A review of the scientific literature showed that most of the focus on how to feed the world is on increasing food production through technological advances, whereas attention on "reducing the food demand through dietary changes to less-intensive patterns has remained constant and low" [51].

In either case, increased crop yields could meet the needs of the growing population without significantly increasing croplands. Agricultural yields have increased without a significant increase in agricultural land use in the past. For example, "between 1961 and 2000, the global population more than doubled and the per capita cereal consumption increased by 20%; however, the area of harvested cereals increased by only 7%, largely because cropping intensities increased" [52]. [53] found that by maximizing crop yields (i.e., closing yield gaps), the global crop production could increase by 45–70% with the same land use but with considerable changes in nutrient and water management. This increase in productivity however can be accompanied by increased pressure on the land and more intense environmental impacts [44, 45] and needs to be balanced with the impacts of increasing cropland.

4.1.2.2 Dietary changes Studies show that without a significant shift to less impactful diets, projected production efficiencies alone will not be enough to meet the future food demand without increasing the total environmental burden of food production [54]. However, changing diets to a globally adequate diet of 3000 kcal per capita per day, with 20% animal kcal, would allow an additional 2.1–3.1 billion people to be fed in 2050 if yield gaps are closed [55]. Another study showed that a transition towards more-sustainable production and consumption patterns could support 10.2 billion people within the planetary boundaries given, if cropland is spatially redistributed, water and nutrient management improved, food waste reduced, and dietary changes imposed [56].

4.1.2.3 Food waste Another important consideration to improve the efficiency of food systems is the reduction of food waste. The energy embedded in global food losses is 38% of the total final energy consumed by the whole food supply chain [57]. This means that more than 10% of the world's total energy consumption is food that is lost and wasted. By one estimate, the food losses and waste that occur every year generate more than 3.3 gigatonnes of CO_2 equivalents [58, 59] determined that an additional 1 billion people could be fed if food waste was halved, from 24 to 12%. The World Resources Institute reported that a 25% reduction in food waste would push food production 12% closer to the level necessary to feed the world in 2050, and would reduce the amount of increased agricultural land needed by 27%, inching closer to fully closing the land gap [60].

4.1.2.4 Demand for animal protein "Most developed countries have largely completed the transition to livestock-based diets, although it is unlikely that all developing countries—including India—will shift to levels of meat consumption typical of western diets in the foreseeable future" [45]. The FAO 2030 Agriculture Outlook suggests that near-saturation levels of meat consumption, as well as health and sustainability concerns, might limit the growth of animal protein consumption in high-income countries, particularly reducing the demand for beef. However, the demand for poultry is expected to increase in high-income countries in the move to a more sustainable and healthy diet, and in middle- and lower-income countries because it is the most economic animal protein (this will also circumvent religious reasons for the non-consumption of meat, such as the consumption of beef and pork in India and Muslim countries, respectively). However, it is estimated that over the next decade, any gains (emissions-wise) made from the reduced demand for animal products in developed countries due to increases in vegetarianism or veganism will be offset by the increased consumption of meat in middle-income countries due to lifestyle changes and increasing per capita caloric consumption.

4.1.2.5 Environmental impacts Increased meat production impacts land use in terms of increased pastureland and increased cropland. Increased livestock production (especially sheep and goats), will lead to a conversion of marginal croplands to pastureland by 1.2 Mha in Sub-Saharan Africa and by 3.22 Mha in North America [43].

Table 7 Non-energy emissions from the agriculture sector

Parameter	Unit	2019	2025	2030	2035	2040	2050
			Calculated results				
Agriculture—AFOLU	[Mt CO_2/year]	663	326.41	− 127.36	− 218.02	− 118.71	− 231.82
Agriculture: synthetic and organic fertilizer	[kt N_2O/year]	7827	6849	6300	6091	6126	6047
Agriculture (incl. food waste)	[Mt CH_4/year]	153	118	96	88	86	79
Agriculture: ammonia	[Mt NH_3/year]	22	22	21	21	21	20
Agriculture—total non-energy GHGs	[Mt CO_2e/year]	6838	5330	4156	3802	3870	3562

Besides land use change, the other main contributor to agricultural emissions is methane emissions from the enteric fermentation in livestock. Meat rich diets (particularly beef) have a much larger impact on the environment and higher GHG emissions: "methane, from enteric fermentation; CO_2, which is released from the clearing of forests for pasture; and nitrous oxide (N_2O), which is generated in feed production" [44]. Diets with a smaller meat component have significantly lower emission intensities. Under the current policy regime, the FAO 2030 Agriculture Outlook projects that agricultural GHG emissions will grow by 4% between 2018 and 2020 and 2030, with livestock accounting for more than 80% of this global increase [43].

Non-energy-related carbon emissions are calculated with the Generalized Equal Quantile Walk (GQW) method, the land-based sequestration design method, and the carbon cycle and climate model (Model for the Assessment of Greenhouse Gas Induced Climate Change, MAGICC) [27]. The model also accounts for other GHG gas emissions arising from the enteric fermentation of livestock (CH_4), crop residues and fertilizers, and manure management (N_2O). An industry sub-sector share has been assigned for each GHG, as explained in the attached supplementary material. Only a small part (20%) of the CO_2 emissions attributable to changes in land use are assigned to the agriculture sub-sector, with 80% assigned to forestry. Table 7 shows the breakdown of the different emission sources in agriculture. These emissions are multiplied by the global warming potential of the other GHG gases to obtain the total CO_2 equivalents (CO_2e) for the sector.

4.2 Overview of global forestry and wood sector

The following section gives a brief overview of the global *forestry and wood* sector in terms of the key economic parameters and details of its GICS classification.

Economic significance: Forestry contributes to food security, livelihoods, and well-being; supports terrestrial ecosystems and biodiversity; provides (human)-life-sustaining ecosystem services; and acts as a carbon sink. Value is also added by some of the manufacturing sectors supported by forestry. In 2018, wood and wood products contributed 183 billion USD and paper and paper products contributed 324 billion USD to the global economy. Together with agricultural manufacturing, this is about 18% of the value added in total manufacturing globally [32].

Global Industry Classification Standard: The corresponding GICS sectors for the *forestry and wood* sector occur under 1510 Materials and the sub-groups 151050 Paper and Forest Products, 15105010 Forest Products, and 15105020 Paper Products, as shown in Table 3 [33].

4.2.1 Energy demand for the global forestry, wood, and wood products sector

The sectoral final energy consumption of forestry has remained stable over the last three decades, and half of this demand is met by oil products. The energy demand of the forestry and wood sector was calculated with the same methodology as for the agricultural and food-processing sector. The IEA Advanced Energy Balances show the wood and wood products separately, but combine the energy demand for forestry with that for agriculture. The energy demand for forestry was calculated both as the energy intensity (Table 9) multiplied by the global GDP for this sector, as shown in (Table 8), and by subtracting the calculated energy for agriculture (see previous section) from the combined energy demand for agriculture and forestry provided by IEA. With this repeated calculation, the energy intensity for forestry and agriculture, taken from the literature, was calibrated to the IEA cumulative statistical value for agriculture and forestry. The economic values for forestry were taken from FAO 2015 [61].

Selected energy intensities of the wood products and paper industry, as well as the average energy intensities, were used to calculate the energy demand for the forestry industry and the wood and wood products industry. For forestry, it is assumed that the improvement in energy efficiency per year will be relatively small, at only 0.25% per year, because this industry is already highly automated [62].

The wood and wood products industry, as defined in the IEA statistic, includes the manufacture of wood and

Table 8 Global economic development of the forestry, wood, and wood products industry

Parameter	Unit	2019	2025	2030	2035	2040	2050
		Input assumptions					
Forestry industry—economic value	[bn $]	155	187	221	261	300	390
Wood industry—economic value	[bn $]	143	183	216	255	293	381
Pulp and paper industry—economic value	[bn $]	117	150	177	209	240	312
Round wood	[million m^3]	3969	3993	4013	4033	4053	4094
Variation compared with 2019	[%]	0.0%	0.6%	1.1%	1.6%	2.1%	3.1%
Sawn wood	[million m^3]	489	492	494	497	499	504
Variation compared with 2019	[%]	0.0%	0.6%	1.1%	1.6%	2.1%	3.1%
Pulp for paper	[million tonnes]	194	195	196	197	198	200
Variation compared with 2019	[%]	0.0%	0.6%	1.1%	1.6%	2.1%	3.1%
Paper and paperboard	[million tonnes]	404	407	409	411	413	417
Variation compared with 2019	[%]	0.0%	0.6%	1.1%	1.6%	2.1%	3.1%

Table 9 Assumed energy intensities for the forestry, wood, and wood products industry

Energy intensities		2019	2025	2030	2035	2040	2050
			Input assumptions				
Forestry	[MJ/$GDP]	3.38	3.34	3.30	3.25	3.21	3.13
Assumed efficiency increase per year	[%/year]		0.25%	0.25%	0.25%	0.25%	0.25%
Wood and wood products (incl. paper) Industry	[MJ/$GDP]	25.62	24.4	22.2	21.1	20.0	19.3
Assumed efficiency increase per year	[%/year]		1%	1%	1%	0.5%	0.5%

Table 10 Results: energy demand for the forestry and wood products industry

Parameter	Unit	2019	2025	2030	2035	2040	2050
			Calculated results				
Forestry—energy demand	[PJ/year]	832	923	992	1063	1114	1197
Forestry—electricity demand	[PJ/year]	74	5	11	22	44	176
	[TWh/year]	20	2	3	6	12	49
Forestry—heat and fuels	[PJ/year]	578	646	694	744	780	838
Energy demand—wood and paper	[PJ/year]	7039	7791	8737	9779	10,695	13,330
Wood and paper—electricity demand	[PJ/year]	2165	2007	2357	2763	3165	3944
	[TWh/year]	893	885	929	976	1025	1130
Wood and paper—heat and fuels	[PJ/year]	4873	5532	6204	6943	7593	9464

of products made of wood and cork, except furniture, and the manufacture of articles of straw and plaiting materials, as classified under the United Nations International Standard Industrial Classification of All Economic Activities [33] (Table 9).

The calculated total final energy demand, further broken down to the electricity and heat/fuels demand for the forestry and wood products industry, is shown in Table 10. The processing of wood to wood products requires considerably more energy than forestry activities. For this reason, in developing the 1.5 °C energy pathway, the energy efficiency in this area is given greater importance than that for timber harvesting.

4.2.2 Land-use demand for forestry

Unlike agricultural land, forest land has been declining over time. In 2020, the total forest land was over 4 billion ha [27]. An estimated 420 million ha of forest was lost through deforestation between 1990 and 2020, although the rate slowed over the period and the net reduction in the global forest area in this time was about 178 million ha [63].

Agriculture has driven an estimated 80% of the deforestation worldwide [47]. "The global expansion of agricultural land has stabilized over the last 20 years at around 4.9 billion hectares for global food production" [44]. The

Table 11 Results: non-energy GHG emissions in the forestry industry

Emissions		2019	2025	2030	2035	2040	2050
Non-energy GHG emissions							
			Calculated results				
Forestry—AFOLU	Mt CO/year	2651	1306	− 509	− 872	− 475	− 927
Change to 2019	[%]	0	− 51%	− 119%	− 133%	− 118%	− 124%

rate of net forest loss has been substantially decreasing as deforestation declines in some countries, whereas an increase in forest area has been seen in others countries, due to afforestation and the natural expansion of forests. However, in the last decade, there has been a reduction in the rate of forest expansion [63].

FAO estimates that, 30% of all forests are used for production. Of this 30%," about 1.15 billion ha of forest are primarily used for the production of wood and non-wood forest products, and another 749 million ha are designated for multiple uses". In contrast, only 10% is allocated for biodiversity conversation, although more than half of all forests have management plans [63].

Regional inequalities are not reflected in this global overview. In tropical and sub-tropical regions, annual forest losses still amounted to 7 million ha in 2000–2010, whereas the agricultural area expanded by 6 million ha per year in the same period (FAO, 2016). The largest reductions were observed in Brazil (down 53.2 million hectares) and Indonesia (down 27.5 million hectares). However, small increases were seen in Europe and the United States. The largest increase was in China, where the forest area was 51.2 million hectares larger in 2015 than in 1990 [35].

There is potential for 'nature-based solutions' to remove CO_2 from the atmosphere at the gigatonne scale, with potentially significant co-benefits [27]. Simulations of nature-based approaches, such as forest restoration, reforestation, reduced harvest, agroforestry, and silvopasture, were combined and found to sequester an additional 93 Gt carbon by 2100. According to [64], this would require an additional 344 million ha of land for reforestation. The key pathway for managing land-use change is reforestation, which is limited to biomes that will naturally support forests, by identifying previously forested land in close proximity to intact or degraded natural forests. This comprises of 274 Mha of land in proximity to intact forests in sub-tropical and tropical forest biomes, and another 70 Mha identified in temperate biomes.

Decarbonization pathways are being developed at the global level. At this level, there is little conflict between the competing uses of cropland, pastureland, and forests for carbon removal. Adopting nature-based approaches, such as agroforestry or silvopasture, where trees are integrated into cropland or grazing lands, will help to increase the carbon stock while meeting the increasing demand for forestry and agricultural products. It should be noted that a lot of deforestation and the capacity and demand for increased agricultural and livestock products will occur in tropical and sub-tropical regions, often in developing countries. At the local level, there must be a more nuanced approach to addressing the balance between environmental, economic, and well-being outcomes.

The OECM model also calculates the non-energy GHG emissions from the forestry sector, as shown in Table 11. The OECM 1.5 °C net-zero pathway is based on efficient energy use and renewable energy supply only—leading to full energy decarbonization by 2050. No negative emission technologies are used and the OECM leads to zero energy-related carbon emissions. The model assumes no net deforestation from 2030 onwards, and the adoption of nature-based approaches to land-use management. Therefore, from 2030 onwards, there will be carbon removal or negative emissions.

5 Global results: energy supply and emissions

After the energy demand was assessed, the supply was determined. All supply scenarios were developed on the basis of a global carbon budget of 400 $GtCO_2$ between 2020 and 2050, in order to classify as an IPCC Shared Socioeconomic Pathway 1 (SSP1) no- or low-overshoot scenario [4]. For a better overview, the generation mixes for electricity and (process) heat are briefly documented here. The detailed derivation of the generation paths is documented in [11].

Table 12 shows the development of the projected global electricity generation. Coal- and lignite-based power plants will be phased out first, followed by gas power plants as the last fossil-fuelled power-generation technology, after 2040. Solar photovoltaic and onshore and offshore wind, are projected to have the largest growth rates, leading to a combined share of 70% of electricity generation globally by 2050. The overall renewable electricity share will increase from 25% in 2019 to 74% in 2030 and to 100% by 2050, with the full decarbonization of the power sector. Specific CO_2 emissions per kilowatt-hour will decline from 509 to 136 g by 2030. For consistency, the methodology description of the One Earth Climate Model

Table 12 Results: Global electricity supply under the OECM 1.5 °C pathway

		2019	2025	2030	2035	2040	2050
		OECM 1.5 °C electricity generation trajectory					
Coal	[%]	31%	17%	5%	1%	0%	0%
Lignite	[%]	7%	1%	1%	1%	0%	0%
Gas	[%]	24%	20%	15%	8%	4%	0%
Oil	[%]	3%	2%	1%	0%	0%	0%
Nuclear	[%]	10%	7%	4%	2%	0%	0%
Hydrogen (produced with renewable electricity)	[%]	0%	0%	0%	2%	2%	5%
Hydro power	[%]	16%	14%	13%	10%	9%	9%
Wind	[%]	5%	14%	22%	28%	32%	36%
Solar photovoltaic	[%]	2%	18%	30%	37%	36%	34%
Biomass	[%]	1%	3%	2%	2%	1%	1%
Geothermal	[%]	0%	1%	2%	2%	3%	3%
Solar thermal power plants	[%]	0%	1%	4%	8%	10%	10%
Ocean energy	[%]	0%	0%	0%	1%	1%	1%
Renewable share	[%]	25%	52%	74%	89%	95%	100%
Electricity Supply: Specific CO_2 emissions per kWh	[gCO_2/kWh]	509	290	136	53	24	0

Table 13 Results: Electricity supply for the sectors analysed until 2050

Parameter	Unit	2019	2025	2030	2035	2040	2050
		Calculated results					
Agriculture and food processing—electricity: fossil	[TWh/year]	255	180	109	54	26	0
Agriculture and food processing—electricity: renewables	[TWh/year]	83	196	311	414	485	591
Forestry, wood and paper—electricity: fossil	[TWh/year]	187	118	67	31	15	0
Forestry, wood and paper—electricity: renewables	[TWh/year]	61	128	191	240	270	314

Table 14 Results: Heat supply under the OECM 1.5 °C pathway

Industry Process Heat Supply, incl. industry combined heat and power (CHP)	Unit	2019 (%)	2025 (%)	2030 (%)	2035 (%)	2040 (%)	2050 (%)
		OECM 1.5 °C heat generation trajectory					
Coal	[%]	33	18	11	6	0	0
Oil	[%]	14	5	3	1	0	0
Gas	[%]	36	38	25	22	17	0
Renewable heat (bio-energy, geothermal, and solar thermal)	[%]	9	24	32	27	21	25
Electricity for heat	[%]	1	8	22	36	49	60
Heat (district)	[%]	7	6	6	7	7	7
Hydrogen and synthetic fuels	[%]	0	0	1	2	6	8

[1] and the documentation of the development of energy scenarios for industry sectors classified under the Global Industry Classification Standard (GICS) [2] cite the same global electricity supply shares as shown in Table 12.

Table 13 shows the calculated electricity supply structure of the agriculture and food-processing sector and the forestry and wood products industry. Rapid technological changes towards renewable electricity generation are anticipated. The electricity demand will increase with the assumed electrification of heating and machinery over the entire modelling period, leading to a requirement for renewable electricity generation that is about twice as high in 2050 as the total electricity demand in the base year 2019. Both the agriculture

Table 15 Results: heat and fuel supplies for the analysed sectors under the 1.5 °C energy pathway

Parameter	Unit	2019	2025	2030	2035	2040	2050
			Calculated results				
Agriculture—heat and fuels: fossil	[PJ/year]	3434	2820	1805	1326	827	0
agriculture—heat and fuels: renewable electricity and synthetic fuels	[PJ/year]	1987	3238	4703	5651	6482	7855
food processing—heat and fuels: fossil	[PJ/year]	2608	2019	1414	1137	776	0
food processing—heat and fuels: renewable electricity and synthetic fuels	[PJ/year]	1509	2319	3685	4845	6081	8533
forestry—heat and fuels: fossil	[PJ/year]	366	301	193	141	88	0
forestry—heat and fuels: renewable electricity and synthetic fuels	[PJ/year]	212	345	502	603	691	838
wood products—heat and fuels: fossil		3087	2575	1721	1319	859	0
wood products—heat and fuels: renewable electricity and synthetic fuels	[PJ/year]	1786	2957	4483	5624	6734	9464
heat and fuels: renewables share	[%]	37%	54%	72%	81%	89%	100%
Heat and Fuels Supply—Specific CO_2 emissions per kWh	[g CO_2/kWh]	130	90	55	36	23	0
Carbon intensity reduction	[%]		−30%	−58%	−73%	−82%	−100%

Table 16 Results: energy-related CO_2 emissions of the analysed sectors under the 1.5 °C energy pathway

Parameter	Unit	2019	2025	2030	2035	2040	2050
				Calculated results			
Agriculture: Total Energy-related CO_2 Emissions	[Mt CO_2/year]	627	449	258	147	90	0
Agriculture: Emissions—Heat and Fuels	[Mt CO_2/year]	281	217	141	98	67	0
Agriculture: Emissions—Electricity	[Mt CO_2/year]	346	232	117	48	23	0
Food Processing: Total Energy-related CO_2 Emissions	[Mt CO_2/year]	843	557	321	176	71	0
Food Processing: Emissions—Heat and Fuels	[Mt CO_2/year]	219	160	114	87	26	0
Food Processing: Emissions—Electricity	[Mt CO_2/year]	624	397	207	89	44	0
Forestry: Total Energy-related CO_2 Emissions	[Mt CO_2/year]	58	18	12	9	6	0
Forestry: Emissions—Heat and Fuels	[Mt CO_2/year]	21	16	11	7	5	0
Forestry: Emissions—Electricity	[Mt CO_2/year]	37	2	1	1	1	0
Wood and Paper: Total Energy-related CO_2 Emissions	[Mt CO_2/year]	630	396	221	120	73	0
Wood Products: Emissions—Heat and Fuels	[Mt CO_2/year]	175	139	94	69	49	0
Wood Products: Emissions—Electricity	[Mt CO_2/year]	455	257	126	51	24	0

Table 17 Results: *Scope 1*, *2*, and *3* emissions of the analysed sectors under the 1.5 °C energy pathway

Parameter	Unit	2019	2025	2030	2035	2040	2050
Agriculture, food processing: *Scope 1*	[Mt CO_2eq/year]	343	272	184	134	95	0
Agriculture, food processing: *Scope 2*	[Mt CO_2eq/year]	971	632	326	139	68	0
Agriculture, food processing: *Scope 3*	[Mt CO_2eq/year]	6838	5330	4156	3802	3870	3562
Forestry, wood products—Scope 1	[Mt CO_2eq/year]	196	155	105	76	54	0
Forestry, wood products—Scope 2	[Mt CO_2eq/year]	492	259	128	52	26	0
Forestry, wood products—Scope 3	[Mt CO_2eq/year]	2651	1306	−509	−872	−475	−927

and forestry sectors have significant potential for on-site power generation using bio-energy and bio-waste/wood for power and heat production.

In terms of heat production, although the phase-out of coal is a priority objective to reduce specific CO_2 emissions, electrification, especially for low- (< 100 °C) and medium-level (100–500 °C) process heat, will be extremely important in achieving decarbonization (Table 14). Decreasing from 130 gCO_2/kWh to 55 g/kWh CO_2 in 2030.

In comparison with the forestry and wood products sector, the agriculture and food-processing industry has significantly higher heat and fuel demands. Table 15 shows the supply of heat and fuels, broken down to fossil and renewable sources, for the agriculture and food-processing industry and the forestry and wood products sector.

The decarbonization of electricity and heat generation and the remaining fuels required will allow the industries analysed here to achieve zero energy-related carbon emissions by 2050. The heating and fuel sector will have higher carbon emissions than the electricity sector between 2019 and 2050 (Table 16).

Table 17 shows the *Scope 1*, *2*, and *3* emissions of the analysed sectors under the 1.5 °C energy pathway. This includes not only the primary production of the agriculture and forestry sector, but also the related industrial sectors of the food-processing and wood products industries, respectively. This wider sector has significantly higher *Scope 3* emissions than *Scope 1* or *2* emissions.

6 Conclusion

Calculating the *Scope 1*, *2*, and *3* emissions for the *Agriculture and Food* and *Forestry and Wood Products* industries on a global level was possible with the simplified OECM methodology and publicly available data. We have shown that both sectors can decarbonize their energy-related *Scope 1* and *2* emissions with a combination of energy efficiency and a shift to a renewable energy supply. Technologies are available to provide the required electricity with renewable electricity for both sectors. Heavy-duty machinery for harvesting food products, such as crops, or timber are currently almost entirely based on fossil-fuel-driven combustion engines. However, bio-fuels and—after 2030—electric vehicles are assumed to be available to reduce energy-related CO_2 emissions to zero by 2050.

Food processing, in particular, requires process heat, most of which was supplied by fossil-fuel-based technologies in 2019. A significant increase in the electrification of process heat generation is assumed to occur. To achieve the overall CO_2 emissions targets, the electricity generation under the OECM pathway will increase the average global renewable electricity share from 25% in 2019 to 74% in 2030. Although the transition to renewables under the OECM 1.5 °C pathways that phase-out energy-related *Scope 1* and *2* emissions are ambitious, the implementation of the assumed *Scope 3* emissions pathways is significantly more challenging.

We found that industry-specific data for energy intensities, although available (especially for the food sector), are often incomparable because they are based on different assumptions and/or methodologies. Therefore, we recommend the standardization of the calculation and reporting methodologies for industry-specific energy intensities for the various technical processes. Furthermore, industry-specific energy statistics, including those for the sub-sectors of industries classified under the GICS system, would significantly enhance the level of detail available for setting net-zero targets in the future.

The management of forests, croplands, and pastures can lead to both the emission and sequestration of CO_2 and other GHGs. The need to feed a population of 9 billion in 2050 will exert significant demands on the global agriculture and food systems. Advances in technology, particularly the increasing role of renewable energy in the agri-food sector, will help to reduce the energy emissions (i.e., the *Scope 1* and *Scope 2* emissions) of the sector. However, given the crop intensification and agricultural expansion required to meet these food demands, it is expected that the agriculture sector will be unable to achieve zero emissions of non-energy GHGs by 2050. Improving soil management, reducing the yield gap, and initiating substantial shifts in dietary and nutritional patterns will help to reduce some *Scope 3* emissions. However, an increase of agricultural land at the expense of forests and/or their expansion in order to achieve negative emissions is likely if crop yield efficiencies cannot be improved. Further research is required on the individual contributions of each of these pathways to the complete decarbonization of the sector.

Nature-based approaches, particularly reforestation, also offer offset options. With an increasing focus on saving and regenerating forests, the forestry sector can not only become carbon neutral but carbon negative, as early as 2030. The abolition of carbon emissions or the achievement of negative emissions between 2030 and 2050 will compensate for the unavoidable process emissions in other sectors, such as the cement and steel industries.

The authors found a lack of policy mechanisms to unlock the large potential for nature-based solutions to create carbon-sinks, although the scientific literature confirms the significant role of land-use emissions in climate-mitigation pathways (IPCC 2021a). More research is required into the compensation mechanisms for process emissions and their potential roles in the implementation of nature-based solutions.

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Declarations

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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