METHODOLOGY OF THE TIMES-AFOLU MODEL

October 2025

Energy Modelling Lab Aps

Refshalevej 163A, 1.

1432 Copenhagen K

CVR: 40941622

Content

1 Introduction

As nations confront the urgent imperative to address climate change and transition toward carbon-neutral economies, energy system modeling has become indispensable for informing policy decisions and conducting scenario analysis. Despite its critical importance, the Agriculture, Forestry, and Other Land Use (AFOLU) sector has received insufficient attention in existing modeling frameworks, even though it exerts substantial influence on energy systems and climate mitigation pathways. This methodology note presents an approach to bridge this gap by developing a comprehensive AFOLU module for TIMES, thereby enhancing the model's capacity to support integrated long-term scenario analysis.

The AFOLU sector plays a pivotal role in climate change mitigation and profoundly influences energy system planning. Critical questions regarding forest carbon sequestration potential, irrigation system optimization, and land allocation for bioenergy production demand rigorous analytical frameworks. The primary methodological objective is to develop a standardized, flexible AFOLU module that integrates seamlessly with TIMES models. This advancement provides the ETSAP community with enhanced modeling capabilities to conduct holistic scenario analysis that captures the complex interdependencies between energy systems and the AFOLU sector.

The methodology incorporates several key components. Water resource tracking will be implemented to account for competing demands and availability constraints. Greenhouse gas emissions or uptake from livestock, crop production, and forests will be comprehensively accounted for and subject to optimization within the modeling framework. Thereby, the projection of AFOLU technologies, such as the evolution of crop types, livestock, and manure management in response to climate change, is found.

The primary objective is to develop an AFOLU module capable of generating decarbonization pathways while accounting for emissions, water use, and land use changes associated with AFOLU activities. To ensure compatibility with existing TIMES implementations, the AFOLU components are modeled using conventional energy system optimization model (ESOM) structures – namely commodities, processes, and their associated parameters (efficiency, costs, emission factors). This design ensures that each stand-alone AFOLU instance can be integrated into TIMES models without requiring code modifications.

Throughout the development process, flexibility and adaptability for national-level implementations remain paramount considerations. Consequently, the module is constructed in accordance with established AFOLU activity data and emissions accounting frameworks, ensuring consistency with IPCC guidelines for greenhouse gas inventory preparation and reporting.

The model is available here: https://github.com/Energy-Modelling-Lab/TIMES-AFOLU/tree/ReleaseTag

This report describes the methodology used for the integration of AFOLU into the TIMES modelling framework, together with the data requirements and technical assumptions made to facilitate the modelling.

2 Model structure

The AFOLU sector representation adopts a flow-based approach consistent with the TIMES framework, ensuring standardized classification of commodities, processes, and flows. The conceptual structure of the agriculture module is illustrated in the flowchart shown in Figure 1.

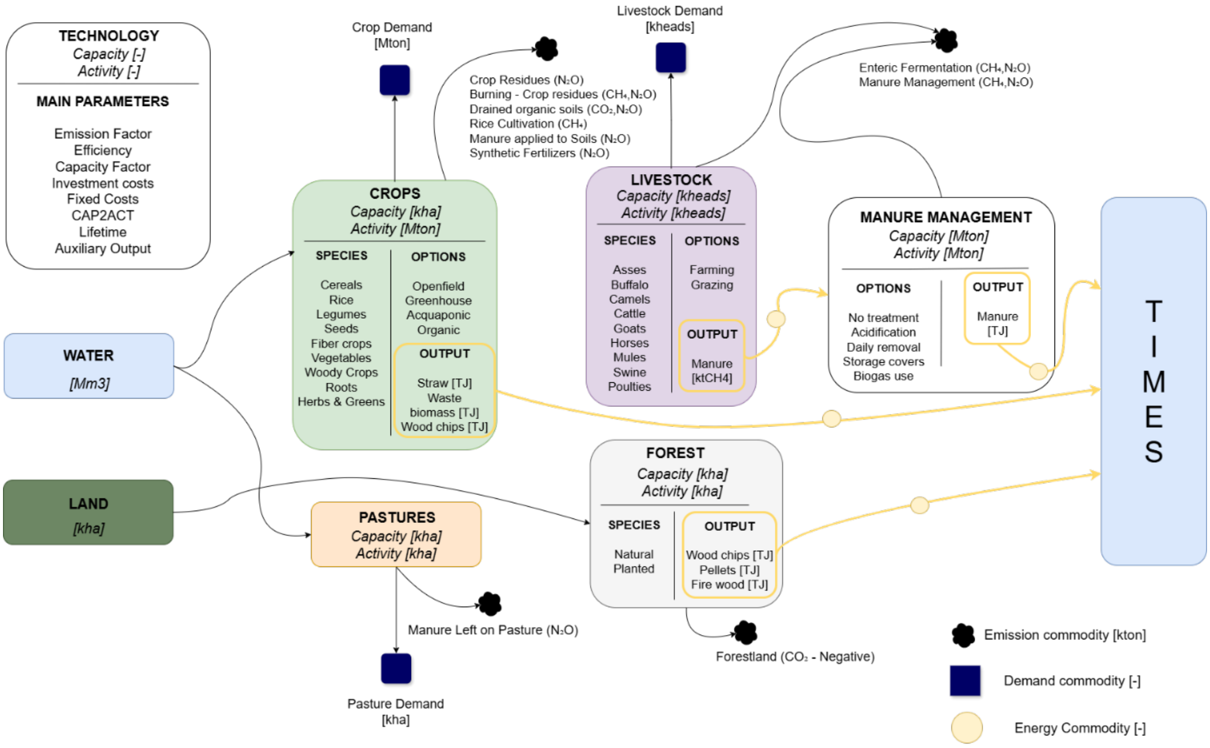

Figure 1: AFOLU Reference Energy System (RES) illustrating the flow of primary commodities through transformation processes to final commodities

The AFOLU system is modelled through three key elements: (1) supply-side commodities, (2) technological processes, and (3) service demands encompassing livestock, crops, forests, and pasture outputs. The energy sector meets AFOLU's energy needs, while AFOLU supplies bioenergy commodities to the energy sector.

2.1.1 AFOLU Reference Energy System

The AFOLU Reference Energy System can be conceptualized as a series of interconnected layers. The primary commodities layer encompasses land and water mining that can be used for feeding to the following transformation process layer.

The transformation processes layer converts extracted resources into intermediary and final products:

- Cropland supports the cultivation of diverse crop types, e.g., cereals, rice, legumes, vegetables, and woody crops, using various farming methods (open-field agriculture, organic methods, greenhouse cultivation, and hydroponics).
- Livestock systems accommodate multiple species from cattle to poultry and produce animals to the demand side and manure for manure treatment.
- Manure management includes different manure management options: no treatment, acidification, daily removal, storage covers, biogas use, and combinations of these.
- Pastureland facilitates both natural regeneration and managed grazing systems
- Forestland provides wood in the form of wood chips, pellets and firewood, and contributes to ecosystem services like carbon sequestration.
- Organic residues, such as straw, and wood byproducts, can be redirected into energy production systems, such as anaerobic digesters and biomass plants, supporting circularity and resource efficiency.

The final commodities layer illustrates the outputs that meet societal demands, including food (crops, livestock) and pasture-based resources.

The framework tracks emissions across the processes, including livestock-related sources (manure management, enteric fermentation), cropland activities (fertilizer use, manure application), and forestry (carbon stock changes).

Processes transform natural resource inputs into outputs while generating emissions. They consume land (kha) and water (Mm^3) as key inputs, defined by two parameters: capacity-to-activity ratio (CAP2ACT), linking available capacity to maximum activity, and efficiency (EFF), measuring input-to-output conversion. For crops, CAP2ACT represents yield; for livestock, forests, and pastures, it equals 1. Efficiency estimates water consumption through irrigated area as a proxy. Emissions (CO_2, CH_4, N_2O) are calculated based on process activity, distributed over cultivated area for crops and related to production via yield data.

Process outputs include main products (crop yields, livestock products, forest goods) satisfying demands, and byproducts (straw, waste biomass, manure, wood) serving as secondary resources in the energy system. Two process types exist: base-year processes (cost-free, reflecting current practices and historical trends) and alternative processes (including investment, operation, and maintenance costs, with modified resource use and emissions for mitigation). Mitigation options for crops and livestock reduce emissions through technological or organic practices, while forests offset emissions from other sectors.

2.2 Demand components

Similarly to all other TIMES models, the AFOLU sector is driven by exogenous demands specified by a list of sectoral demands, actual values in the base year (calibration), and values for all milestone years (projections). In the proposed version of the model, as illustrated in Table 1, there are 13 demands for livestock, 9 for crops, and a generic one for pasture.

Table 1: Demand components

Sector	Process	TIMES demand name	Unit
Livestock	Asses	AGRLIVASSDEM	kheads
	Camels	AGRLIVBUFDEM	
	Cattle, dairy	AGRLIVCAMDEM	
	Cattle, non-dairy	AGRLIVCADDEM	
	Goats	AGRLIVCANDEM	
	Horses	AGRLIVGOADEM	
	Mules and hinnies	AGRLIVHORDEM	
	Sheep	AGRLIVLLADEM	
	Buffalo	AGRLIVMULDEM	
	Swine, breeding	AGRLIVSHPDEM	
	Swine, market	AGRLIVSWBDEM	
	Llamas	AGRLIVSWMDEM	
	Poultry	AGRLIVPOUDEM	
Crops	Cereals	AGRCRPCERDEM	kt
	Legumes	AGRCRPRICDEM	
	Seeds	AGRCRPLEGDEM	
	Fiber crops	AGRCRPSEEDEM	
	Vegetables	AGRCRPFCRDEM	
	Roots	AGRCRPVEGDEM	
	Herbs and greens	AGRCRPWCRDEM	
	Woody crops	AGRCRPROODEM	
	Rice	AGRCRPHAGDEM	
Pastures	Pasture	AGRGENPASDEM	kha

Forests, which are absent, do not have a demand value but are instead used to provide negative emissions, if needed. Therefore, an increase in forest area is endogenously generated by the model if requested by the imposed decarbonization goals, while their already existing presence is imposed as NCAP_PASTI constraints and assumed constant (Lifetime equal to 100 years).

2.3 Supply component

Two key resources have been identified as relevant to the agriculture sector: land and water. As all the traditional commodities in TIMES, water is obtained through a mining process (MINWTR) that provide its primary input. Land is also mined through a mining process (MINLND) but is only used as input to the forest as it has no direct water usage. For crops and pasture, land is only accounted for through the capacity of the technology. In this way, the activity of the process is strictly linked to the consumed land trough the Capacity to Activity parameters. This methodological choice is better detailed in Section 2.4. Moreover, while water have an economic value, no price has been assigned to it in this phase of the model. This can be applied by the user directly. For land, the rental price of land is included in the investment cost of the technologies.

2.4 Crops

Crops represent the second most impacting component of the AFOLU sector in terms of emission, and the first in terms of direct water and land use [1]. Therefore, the level of detail in terms of modelling should reflect this relative importance. The model can account for land and water use by crop production, as well as their related emissions. According to actual (base year) and future (future years) demand projections, the TIMES-AFOLU model retrieve the necessary natural resources consumption and emissions flows, optimizing according to the best technological options. Always following the minimum cost pathways of the main model.

This chapter describes which data are necessary to model the crop sector (2.4.1). Then, section 2.4.2 describes the detailed modelling of the crop technologies, highlighting how data from 2.4.1 are linked to the TIMES technology and commodity main parameters. Finally, in the How to Guide, an example is provided on how to retrieve crops data and prepare the input for VEDA.

2.4.1 Data requirements

For each modelling instance, crops must be characterized in terms of capacity, activity, emissions, and resource flow efficiencies. This ensures alignment with the TIMES process modelling structure [2]. However, unlike sectors such as industry or transport, where well-defined technological processes and data are readily available, crops – along with livestock, pastures, and forests – do not fit neatly into this framework. Their original structure is not the process based as if they were industrial technologies. Therefore, the first step is to gather data on the key characteristics of these entities, particularly those who can be linked to TIMES parameters.

For each nation and year, the data required to correctly model the crop sector are reported in Table 2. Division is made by type of data, unit of measurement and related excel file on which the data must be filled. The elements of Table 2 can be sourced from various datasets. For OECD countries, the most precise and reliable data source is the UNFCCC database [3]. This provides robust, standardized data for countries within the OECD region. For all countries, particularly those outside the OECD area, the primary source of data is FAOSTAT [4], which offers comprehensive global coverage on agricultural and environmental metrics. In the How to Guide it is described how to fill the model using the data from FAOSTAT.

Table 2: Data entry for crop sector

Data	Unit of Measurment	Excel Sheet
Area harvested by crop and year*	[kha]	Input data - crop
Production by crop and year*	[Mton]	Input data - crop

Emissions by year (N2O) - Crop Residues	[kton]	Input data - emissions
Emissions by year (CH4) - Burning - Crop residues	[kton]	Input data - emissions
Emissions by year (N2O) - Burning - Crop residues	[kton]	Input data - emissions
Emissions by year (N2O) - Synthetic Fertilizers	[kton]	Input data - emissions
Water requirements and Irrigation split percentage by crop and year	[Mm3 - % of irrigation by crop]	Input data – irrigation shares (already filled with global values) Calculations - water

The model accounts for all three emissions reported by the IPCC: CO_2, N_2O, and CH_4. The various emission types attributed to land use by FAO and assigned to the crop sector for this study are:

- CO_2: Drained organic soils
- N_2O: Crop residue, burning of biomass, fertilizer and manure applied to soils, and drained organic soils
- CH_4: Rice cultivation and urning of biomass

The different types of emissions are not directly related with the crop types. Therefore, to obtain emission factor for each crop type, it is necessary to set a hypothesis regarding the association of them. In particular, the emissions are provided as total national emissions of a certain GHG [kt], while the area data regarding crop cultivation are expressed in kilo hectares [kha]. However, the emissions in TIMES are set using the EMISSIONS parameter and must be related to the activity, which means that the unit should be kt/Mton. To find this from the given data, it requires the following steps:

1. The overall emissions are first summed up between IPCC categories, obtaining a single overall emissions amount for each GHG type
2. The overall emissions for each GHG are divided by the crop area
3. Given the impossibility of directly relating the emission to a specific type of crop, the simplification introduced here assigns a share of emissions proportional to the cultivated cropland. Since the emission factor should be linked to the activity of the process, the final emission factor is divided by the crop yield

Similarly, the process must be repeated for water, to link the general water use data to the single crop, passing to the percentage of irrigation by crops.

1. For each crop, knowing its area and the irrigation share, the total irrigated area is calculated by taking the irrigation share per type and multiply with the crop area
2. In the same way, knowing the total irrigation water withdrawal and the irrigation share, the total water consumption for each crop is calculated by multiplying the two
3. The specific water consumption by crop is derived by dividing the total water consumption per crop with the irrigated area for the crop and the crop yield by FAO data

2.4.2 Crop modelling

Crop directly consumes water and occupies land, satisfying their related demand and producing residues that can be utilized for bioenergy. According to Figure 2, the generic crop process receives as input the commodity Agricultural Water (AGR_WTR) expressed in Millions of cubic meters (Mm^3). Through the process efficiency, the water is transformed into crop demand commodity, while the land accounted as the capacity of the process.

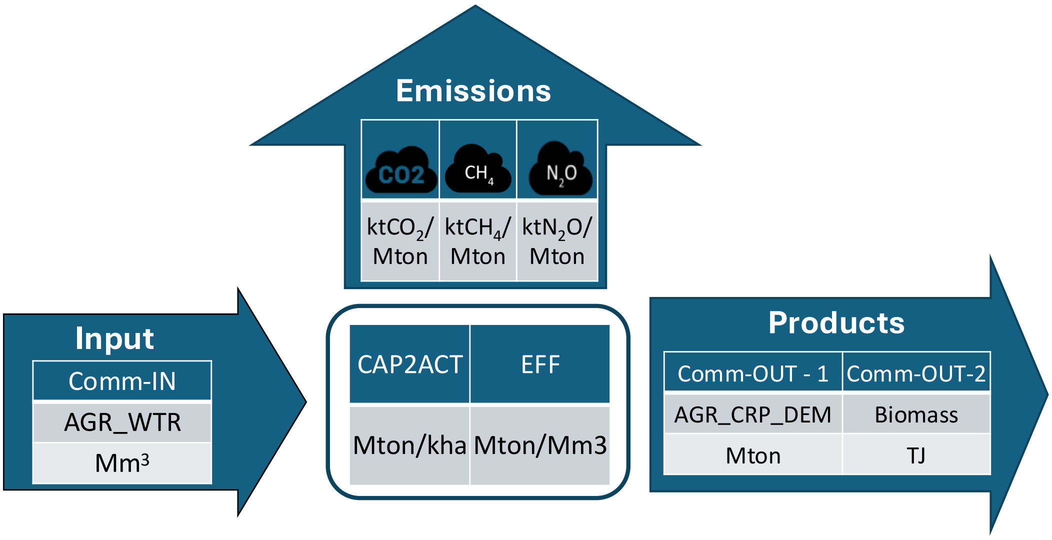

Figure 2: Crop representation

In particular, the land use efficiency, or crop yield, is transferred in the model using the Capacity to Activity (CAP2ACT) parameter. This serves to link the capacity of the crop (kha of cultivated area) to the production required. Similarly, the amount of water consumed is linked to the crop production (Activity of the process, expressed in Mton) thanks to the efficiency parameter. In this way the water, which is a flowing material exchanged between process, is treated as a commodity. Conversely land, which is the fixed base on which the crop process takes place, is treated as a capacity.

In terms of output, the crop directly feed its related demand by producing the commodity as a primary output. Therefore, while the efficiency defines the ratio between the water and the demand commodity, the parameter OUTPUT is used to link the crop production with biowaste (straw, agricultural biowaste or woody biomass) production. The biowaste is converted to an energy commodity that can be linked with a TIMES-model representing the energy system.

2.5 Livestock

Livestock is the highest emitter in the AFOLU sector globally [1], specifically for the enteric fermentation and manure management. Moreover, there is increasing importance in the abatement option for this sector, especially the manure management emissions, which deserve a particular section in this chapter.

This chapter describes which data are necessary to model the crop sector (2.5.1). Then, section 2.5.2 describes the detailed modelling of the crop technologies, highlighting how data from 2.5.1 are linked to the TIMES technology and main parameters.

2.5.1 Livestock data

For each modelling instance, livestock must be characterized in terms of capacity and activity, emissions, and resource flow efficiencies, both as primary commodities input and final demands. The data required to correctly model the livestock sector are reported in Table 3. Division is made by type of data, unit of measurement and related excel file on which the data must be filled. As for crops, the elements of Table 3 can be sourced from various datasets.

Table 3: Data entry for livestock sector

Data	Unit of Measurement	Excel Sheet
Stocks	[An] - animals	Input data - livestock
Enteric fermentation by species (Emissions CH4)	[kton]	Input data - livestock Input data - emissions
Manure management by species (Emissions CH4)	[kton]	Input data - livestock Input data - emissions
Manure management by species (Emissions N2O)	[kton]	Input data - livestock Input data - emissions
Water requirements	[Mm3]	Calculations - water

The emission factor is retrieved based on the population of species and the default emission factors by FAO [5]. The model takes into account the emissions from enteric fermentation (CH_4) and manure management (CH_4, N_2O) emissions

The different types of emissions are linked with the livestock species in the data from FAOSTAT, therefore, it is relatively easy to find the emission factor for each GHG per specie. The emissions for each type of emission are calculated by dividing the emission for each specie with the population of the specie. This is a slight simplification as both of these emissions can be influenced by some mitigation technologies already present in the country of study. If that is the case, and it is possible to obtain data on the implementation share, the emission factor can be recalculated to take it into account.

To link the water use to the single livestock it is necessary to do some recalculations. For each livestock, knowing its population, the total water consumption, and the water consumption factors from literature, the water consumption by species can be calculated as follow:

1. First, estimated water consumption (EWC) is calculated by multiplying water consumption factors (WCF) from literature with the population
2. Then, a calibration is performed between the estimated data and the total real water consumption by livestock, to provide accurate adjusted water consumption (AWC):

$$\mathrm{AWC}_{species,\mathrm{GHG_i}} = \left[\frac{EWC_{species}\left[\frac{liters}{year}\right]}{\sum_{species} EWC_{species}\,[liters]}\right] * \left[\frac{Total\,WC_{real}\,[liters]}{population_{species}\,[heads]}\right]$$

2.5.2 Livestock modelling

Livestock require water and natural resources, particularly crops and other feeding materials, to meet their nutritional needs. In turn, livestock generate by-products such as manure, which can be utilized for biogas production within energy systems. The key distinction between livestock and other agricultural sub-sectors lies in the direct demand livestock impose on both crop production and pastureland, as they consume crops and graze on pastures. From a modelling perspective, this interaction should be represented as stocks of crops and pastureland supporting both farming and grazing livestock, which would result in indirect land use in both sectors. In TIMES, there should be intermediate technologies that transform crop and pasture sectoral output to livestock commodities. However, this interaction is not explicitly modelled. This omission stems from the underlying assumption that a portion of crop demand is allocated not for human consumption but for livestock feed. Since the model's primary objective is to account for emissions, water usage, and land use, it simplifies this relationship by embedding the indirect livestock component within the crop sector. This approach avoids creating additional interconnections that would complicate the model structure and increase data requirements. Further, a lot of countries already today import fodder from other countries. The drawback of this simplification is that it limits the model's ability to optimize and represent land use directly linked to livestock activities. Consequently, it is up to the modeler to develop scenario-specific assumptions regarding livestock, which can be reflected in adjustments to crop and pastureland use patterns in future projections.

The direct land use by livestock differs from that of other AFOLU sub-sectors. In the case of farmed livestock, land use is minimal because farming is treated as an industrial process. The land occupied by farming facilities is negligible compared to the extensive land required for fodder production. Therefore, it is neglected. For grazing livestock, as previously mentioned, pasturelands are assumed to be designated for grazing. Both the land use and emissions associated with these activities are accounted for within the pastureland sub-sector.

The generic livestock process is shown in Figure 3.

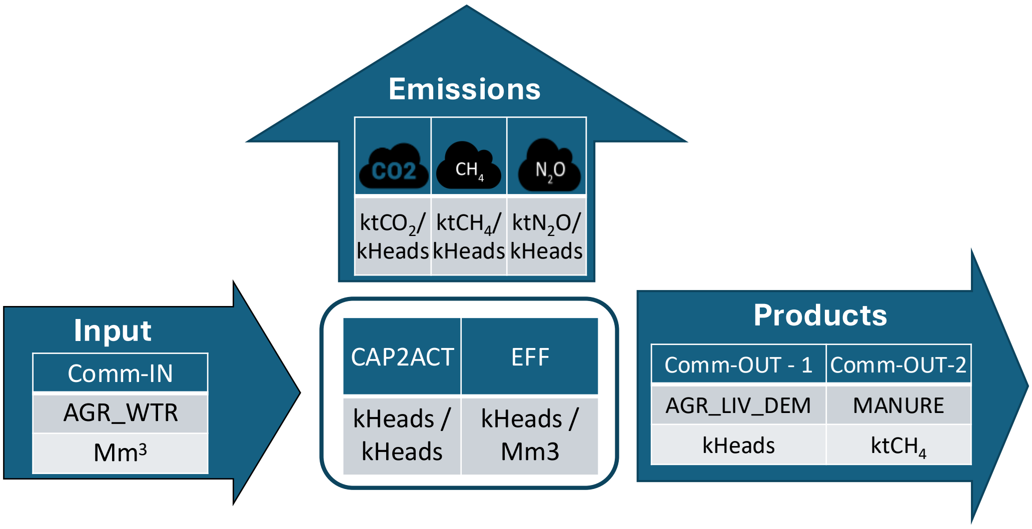

Figure 3: Livestock modelling

The generic livestock receives the commodity Agricultural Water (AGR_WTR), expressed in millions of cubic meters (Mm³), as input. The water use efficiency of the livestock process is then translated into ESOM parameters.

Water consumption is linked to the livestock production process (Activity of the process, expressed in kilotons of livestock products) through the efficiency parameter. As with livestock production, water is treated as a flowing material exchanged between processes and modelled as a commodity. For livestock, the CAP2ACT is equal to 1, meaning that the unit of capacity and the unit of activity are the same (thousand head of livestock).

In terms of outputs, livestock directly satisfies demand by producing livestock commodities. Additionally, manure is generated as a by-product. This waste stream is defined as an energy carrier because it can be used in manure digesters to produce biogas, which can then be fed into the energy system. The efficiency parameter links water consumption to the production of livestock commodities, while the OUTPUT parameter is used to define the amount of biogas generated from the manure produced.

2.6 Pastures

Pastures represent a significant component of the AFOLU sector, particularly in terms of land use and emissions associated with grazing activities[1] . The modeling of pastures must consider their role in land occupation and emissions resulting from grazing livestock, including CO_2, CH_4, and N_2O. Effective modeling should capture the interactions between pasture use and livestock emissions, as well as the potential for carbon sequestration in managed pastures.

This chapter describes which data are necessary to model the pasture sector (2.6.1). Then, section 2.6.2 details the modelling of pasture-related technologies, showing how data from 2.6.1 are linked to the TIMES technology and commodity main parameters.

2.6.1 Data requirements

Pastures must be characterized in terms of capacity and activity, emissions, and resource flow efficiencies, both as primary commodities input and final demands. For each nation and year, the data required to correctly model the livestock sector are reported in Table 4. Division is made by type of data, unit of measurement and related excel file on which the data must be filled.

Table 4: Data entry for livestock sector

Data	Unit of Measurement	Excel Sheet
Land Under permanent pastures and meadows	[kha]	Input data - area
Manure applied on Pastures (Emissions CH4)	[kton]	Input data - emissions
Manure management by species (Emissions N2O)	[kton]	Input data - emissions
Water requirements	[Mm3]	Calculations - water

2.6.2 Pasture Model

Pasture directly consumes natural resources, specifically land and water, to satisfy demand, without involving any transformative processes or secondary outputs. According to Figure 4, the pasture process takes in the commodity Agricultural Water (AGR_WTR), measured in millions of cubic meters (Mm³). However, unlike crops, pasture does not have a yield, as both its capacity and activity are expressed in kilo hectares, simply representing the total pasture area.

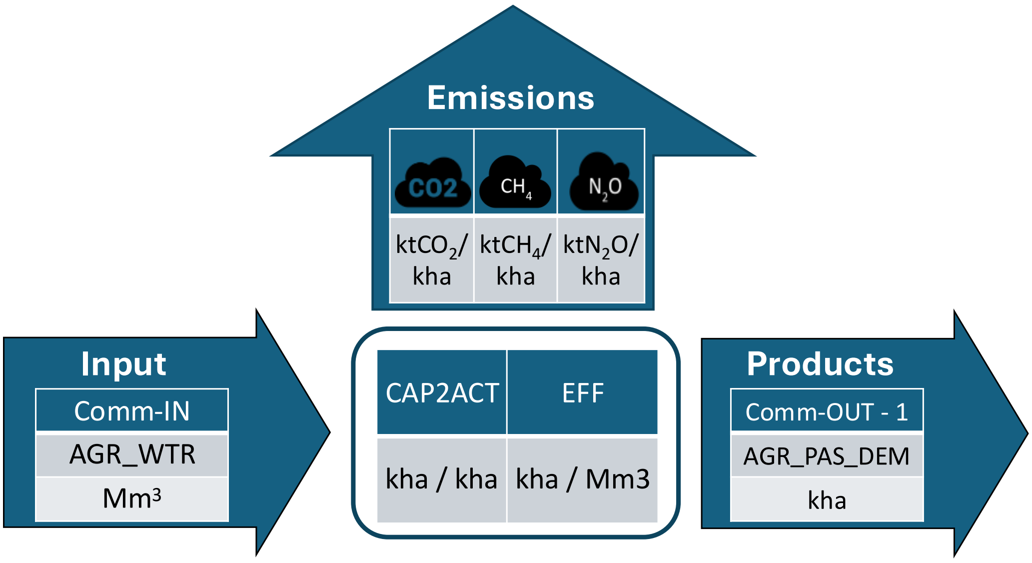

Figure 4: Pasture representation

The land use efficiency is inherent in the Capacity to Activity (CAP2ACT) parameter of TIMES [2], but since both capacity and activity are measured in kilo hectares, they are identical, directly reflecting the demand for pastureland. Water consumption is linked to the activity (pasture area) through an efficiency parameter, treating water as a flowing commodity between processes. However, pasture does not generate any waste or secondary output, making it a straightforward representation of land use for grazing, with no further connections to other sectors.

Emissions factor and water requirement for pasture, similarly to crops, are obtained as follow:

1. The overall emissions are firstly summed up between IPCC categories, obtaining a single overall emissions amount for each GHG emission
2. The emission factor is derived by dividing each type of pasture emission by the pasture area

For pastures, knowing its area and the irrigation share, the total irrigated area is calculated by multiplying the two. In the same way, knowing the total irrigation water withdrawal and the irrigation share, the water consumption for pasture is calculated by multiplying the two. Then, the specific water consumption by pasture is derived by dividing the water consumption for pastures with the irrigated area.

2.7 Forests

Forests are the most significant mitigation option in the AFOLU sector. At the same time, they are the largest source of carbon capture and carbon emission [1]. Concerning the latter, deforestation due to land use change leads to net positive emissions, which the IPCC identifies as the highest impacting sources [6]. Therefore, forest modelling must account for their dual role in both negative emissions and land use change, particularly concerning CO_2 sequestration.

This chapter describes which data are necessary to model the Forest sector (2.7.1). Then, section 2.7.2 details the modelling of Forest-related technologies, showing how data are linked to the TIMES technology and commodity main parameters.

2.7.1 Data requirements

Forests must be characterized in terms of capacity, activity and emissions. For each nation and year, the data required to correctly model the forest sector are reported in Table 5. Division is made by type of data, unit of measurement and related excel file on which the data must be filled.

Table 5: Data entry for forest sector

Data	Unit of Measurement	Excel Sheet
Forestland	[kha]	Input data - area
Forestland (Emissions CO2)	[kton]	Input data - emissions
Net Forest emissions (Emissions CO2)	[kton]	Input data - emissions
Water requirements *Only in case of irrigated forest	[Mm3]	Calculations – water
Forest production	[tons] or [m3]	Calculation - Forest
Forest emission factors	[ktonCO2/kha]	Calculation - Forest

The only data that remains to be filled are the Forest production and the emissions factors that must be obtained by literature, considering the specific forest species present in the selected geographic area.

2.7.2 Forest Model

Forests do not require irrigation, and as a result, the default technology in the model does not include water inputs and associated efficiency metrics. If irrigation is present in specific national instances, it is the responsibility of the modeler to introduce relevant technologies to account for this practice. Only land use is accounted thanks to a land mining technology connected to forests. According to Figure 5, the forest produces three wood products (wood chips, wood pellets and firewood). The split on the wood products is handled by setting an upper bound on the amount of wood chips produced while the split on firewood and wood pellets is decided in the optimization. The products is converted to TJ in a process after the forest technology and can be connected to the energy system after this process.

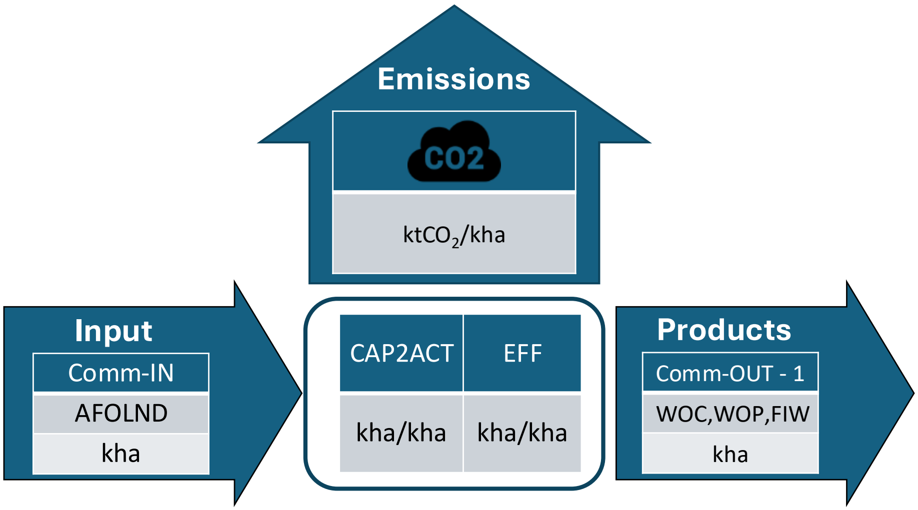

Figure 5: Forest model

Notably, the forest does not generate positive greenhouse gas (GHG) emissions. Instead, it functions as a carbon dioxide sink. The negative emissions factor should be calibrated based on the base year and projected for future years, considering the geographical and technological factors relevant to each case.

3 Mitigation options

3.1 Mitigation options for crops

For crops, a long list of possible mitigation options has been identified [7]. The measures span different soil management techniques, bioenergy with carbon capture and more agricultural side measures to social measures: Like limited urban sprawl and sustainable tourism. Nevertheless, for the purpose of this analysis, only the options that can be modelled in a technologically compatible way and that presents relevant implications in terms of emissions, land and energy are accounted for. Therefore, here there are two kinds of options considered: different cropping techniques and sustainable agricultural practices.

Considering the sustainable agricultural practices, and according to FAO [8], these includes soil carbon management, biochar application, agroforestry, and crop nutrient management. However, for the current version of the model, these mitigation options are not included. In existing literature, a lack of comprehensive techno-economic assessment is lacking, as well as a regionalized dataset about land suitability. To fully account for their impact and potential contributions to greenhouse gas reduction and sustainable agriculture, a more detailed review is required.

We have instead restricted the mitigation options to focus only on cropping techniques. Here we refer to hydroponics, greenhouses and organic cropping, which has shown potential in increasing crop yield, reducing land use, water use and/or emissions ([9], [10]). For these options, in absence of more precise literature, factors have been assumed regarding the improvement compared to conventional cropping. In Table 6 those factors are summarized.

Table 6: Crop mitigation options parameters for greenhouse and hydroponic. Comparison with open field values for yield (CAP2ACT) and water consumption ratio.

Parameter	Tech-type long	Value	Description
CAP2ACT Ratio	Open Field	1	Representing how much more of the crop a greenhouse, hydroponic or organic growing method are producing compared to Open Field
	Greenhouse	3	
	Hydroponics	6	
	Organic	0,75	
Water Ratio	Open Field	1	Representing how much more water consumption a greenhouse, hydroponic or organic growing method have compared to Open Field
	Greenhouse	0.75	
	Hydroponics	0.50	
	Organic	1	

The different cropping technologies are modeled by applying correction factors to yield (CAP2ACT) and water use (EFF) ratios relative to traditional open-field systems. These factors ensure that production outputs, emissions, and natural resource consumption are adjusted proportionally – either directly or indirectly – reflecting the application of these corrections. For organic cropping also the emissions have been updated as the emissions from nitrogen fertilization are excluded from the emissions factor calculation. The general factors are derived from a comparison based on a case study in Jordan, which has been generalized as a hypothesis for all crops. This approach is intended to evaluate the theoretical effectiveness of the measure. Nonetheless, it remains the responsibility of modelers to collect data on region-specific factors and to exclude crop types for which hydroponics or greenhouses options are not feasible (currently these technologies are included on a subset of the crop types).

Concerning the economics of the crop mitigation options, it is differentiated between the options that simply require land expansion (e.g., organic cropping) and the ones that require infrastructure (greenhouses, hydroponics). Regardless of the specific case study, two cost components are accounted for. All the land-intensive technologies are characterized by a fixed cost equal to the country-specific cost of land rent (for the test case, data was found in Eurostat [11]). This means that organic cropping that requires additional land due to lower yield will have higher fixed costs for the same production level. Nevertheless, greenhouse and hydroponic cropping both require additional land and infrastructure. In the absence of a comprehensive database detailing average national or European-level costs for crop mitigation options (e.g., greenhouse systems), cost estimates have been sourced from specific European case studies [12].

3.2 Mitigation option for livestock

This section details the different mitigation options available for the livestock sector. According to the 7th IPCC impact assessment report [1], it identifies in the livestock enteric fermentation and manure management emissions as the most impacting ones, especially in developed countries where no more deforestation is taking place. The estimated technical potential for both the option is 0.5-3.2 GtCO2eq [1]. Therefore, a proper modelling of the abatement option for this sector must be inserted.

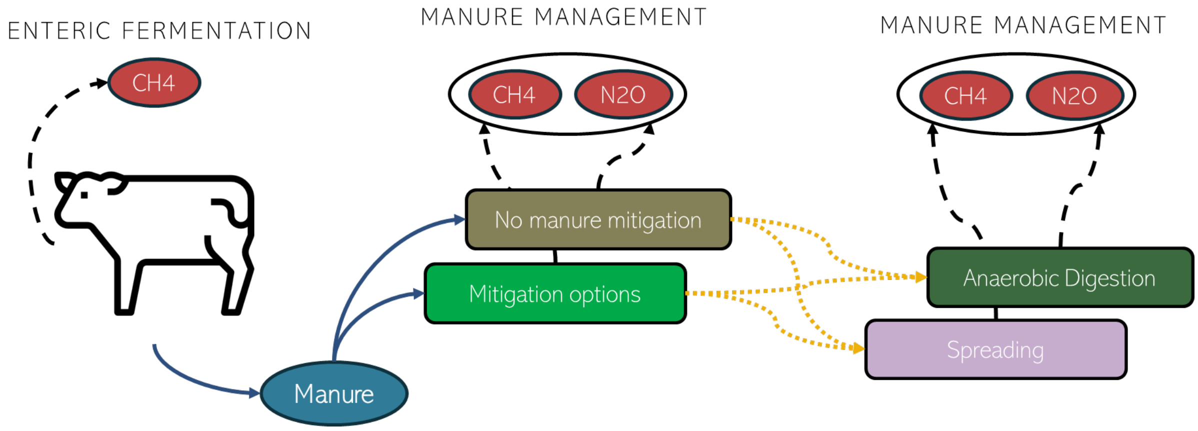

Figure 6: Manure and livestock emission possible pathways.

3.2.1 Enteric Fermentation

Enteric fermentation, a process in ruminant animals like cattle, goats, sheep, and buffalo, is a significant source of methane emissions [13]. Mitigation strategies include direct measures targeting ruminal methanogenesis or improving production efficiency, classified into feeding practices, supplements (such as additives and vaccines), and livestock breeding or husbandry improvements[14]. Chemically synthesized inhibitors show promise, with mitigation potential between 16% and 70%, but challenges such as persistence, costs, and regulatory approval remain. Additionally, administering these inhibitors in pasture-based systems poses difficulties, and CH_4 vaccines are still under development [14]. While developed countries focus on direct technical options, developing nations emphasize improving production efficiency. The global technical potential for reducing methane emissions from enteric fermentation is estimated at 0.8 (0.2–1.2) GtCO2-eq per year, with 0.2 (0.1–0.3) GtCO2-eq per year available at costs below USD 100 per tCO2-eq [14]. Due to the low technology readiness level (TRL) of the available options and the lack of comprehensive data, enteric fermentation is currently omitted from the modeled mitigation options.

3.2.2 Manure Management

Manure management measures target the mitigation of methane (CH_4) and nitrous oxide (N_2O) emissions from manure storage and deposition, addressing both direct and indirect sources, such as the conversion of ammonia and nitrate into N_2O. Integrating manure management with livestock and soil management practices enhances system resilience, sustainability, food security, and prevents land degradation, while also benefiting local environments. These measures have a global technical mitigation potential of 0.3 (0.1–0.5) GtCO2-eq per year, with 0.1 (0.09–0.1) GtCO2-eq per year available at costs up to USD 100 per tCO2-eq [14]. Country-specific strategies reveal various regionally tailored solutions. For example, small-scale anaerobic digestion, solid manure coverage, and daily manure spreading are prominent in Asia, the Developing Pacific, and Africa. Meanwhile, developed countries emphasize large-scale anaerobic digestion, tank/lagoon covers, improved manure application timing, nitrogen inhibitors for urine patches, soil-liquid separation, livestock nitrogen intake reduction, trailing shoe or injection slurry spreading, and acidification [14].

In this case, due to the higher applicability of manure management practices, the availability of relevant case studies, and their established presence in various regions, these manure mitigation options have been included in the modeled mitigation strategies. The mitigation options described by FAO [15] that contain the needed information on abatement potentials are listed in Table 7.

Table 7: Mitigation options for manure management

Mitigation Option	CH_4 Abatement Potential	N_2O Abatement Potential
Daily/weekly manure removal	-55%	-41%

Manure storage covers	-12%	500%
Acidification of manure	-74%	-17%
Anaerobic digestion	-29%	-23%

Since each livestock species is associated with two distinct emission factors—one for CH_4 and one for N_2O—the reduction in emissions varies across species. Applying the same percentage reduction to different livestock technologies leads to different overall emission factor reductions due to the inherent variation in species-specific emissions. It was decided to focus only on manure management of swine and cattle but a similar approach can be used if one wants to extend the model to include more animal types.

The mitigation options have been combined so that there are the following options:

- No treatment
- Daily/weekly manure removal
- Manure storage covers
- Acidification of manure
- Acidification of manure & Daily/weekly manure removal
- Acidification of manure & Manure storage covers
- Daily/weekly manure removal & Manure storage covers
- Acidification of manure & Daily/weekly manure removal & Manure storage covers

All of these can be combined with anaerobic digestion. The emission reduction factor is the product of the involved mitigation options so, e.g., the emission reduction for CH4 for the combination of acidification and daily/weekly removal is $1 - (1 - 55\%) \cdot (1 - 12\%) = 60{,}4\%$.

Regarding costs, local data should be sourced from relevant case studies in literature, as there is considerable variability across regions. However, to be able to include for the test case, data from a Danish study has been used, where the variable O&M and the investment costs is given for cattle and swine. O&M costs are only present for acidification and daily/weekly removal manure removal, while only acidification and manure storage covers have investment costs. Note that anaerobic digestion is handled only with reductions in emissions as the investment costs are assumed to be included in a separate TIMES model including the actual biogas plant. When combining the manure management options, the costs are added together to get to the final cost of the mitigation option.

Another option for livestock is to convert to grassing animals. This is, however, not treated as a real mitigation option as it means that the manure would not be possible to go through the manure management options. It is, however, kept as a possibility in the model, as there could be other reasons for having grassing animals instead of farm animals and is assumed to have a lower use of water. This must be treated together with the pastureland as the grassing animals should be grassing here.

3.3 Mitigation options for pasture and forests

For pasture, there are no direct mitigation options, however, the use of pastures relates to the number of grassing animals and will therefore change when the amount of grassing animals change. This is handled in a user constraint.

For forest, it is possible to extend the current area for forest use, which refers to planting trees that capture carbon during their lifespan. Afforestation, like crop mitigation options, represents a mix cost of land that is occupied (fixed rent cost) plus forest installation (initial investment cost). The data used is based on cost for Sweden [16] and should be updated with country specific data.

4 Bibliography

[1] "Agriculture, Forestry and Other Land Uses (AFOLU)," *Climate Change 2022 - Mitigation of Climate Change*, pp. 747–860, Aug. 2023, doi: 10.1017/9781009157926.009.

[2] R. Loulou, A. Lehtilä, A. Kanudia, U. Remme, and G. Goldstein, "Documentation for the TIMES Model: Part II," 2016. Accessed: Nov. 20, 2023. [Online]. Available: http://www.iea-etsap.org/web/Documentation.asp

[3] "Land Use, Land-Use Change and Forestry (LULUCF) | UNFCCC." Accessed: Mar. 06, 2023. [Online]. Available: https://unfccc.int/topics/land-use/workstreams/land-use--land-use-change-and-forestry-lulucf

[4] "FAOSTAT." Accessed: Sep. 08, 2023. [Online]. Available: https://www.fao.org/faostat/en/#data

[5] "FAOSTAT." Accessed: Sep. 12, 2024. [Online]. Available: https://www.fao.org/faostat/en/#home

[6] IPCC, "Mitigation of Climate Change Climate Change 2022 Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change," 2022. Accessed: Feb. 10, 2023. [Online]. Available: https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf

[7] M. V. Chiriacò *et al.*, "A catalogue of land-based adaptation and mitigation solutions to tackle climate change," *Scientific Data* , vol. 12, no. 1, pp. 1–11, Dec. 2025, doi: 10.1038/S41597-025-04484-0;SUBJMETA.

[8] OECD and FAO, "OECD-FAO Agricultural Outlook 2021-2030." doi: 10.1787/19428846-en.

[9] D. I. Pomoni, M. K. Koukou, M. G. Vrachopoulos, and L. Vasiliadis, "A Review of Hydroponics and Conventional Agriculture Based on Energy and Water Consumption, Environmental Impact, and Land Use," *Energies 2023, Vol. 16, Page 1690*, vol. 16, no. 4, p. 1690, Feb. 2023, doi: 10.3390/EN16041690.

[10] B. Yep and Y. Zheng, "Aquaponic trends and challenges – A review," *J Clean Prod*, vol. 228, pp. 1586–1599, Aug. 2019, doi: 10.1016/J.JCLEPRO.2019.04.290.

[11] Eurostat data browser, "Yearly Land rent price for a year." Accessed: Nov. 30, 2023. [Online]. Available: https://ec.europa.eu/eurostat/databrowser/view/APRI_LRNT__custom_5264437/bookmark/table?lang=en&bookmarkId=0e5713d6-6cad-4033-b9ac-e09b5270c489

[12] J. Lobillo-Eguíbar, V. M. Fernández-Cabanás, L. A. Bermejo, and L. Pérez-Urrestarazu, "Economic Sustainability of Small-Scale Aquaponic Systems for Food Self-Production,"

Agronomy 2020, Vol. 10, Page 1468, vol. 10, no. 10, p. 1468, Sep. 2020, doi: 10.3390/AGRONOMY10101468.

[13] "Agriculture, Forestry and Other Land Uses (AFOLU)," *Climate Change 2022 - Mitigation of Climate Change*, pp. 747–860, Aug. 2023, doi: 10.1017/9781009157926.009.

[14] G. J. Nabuurs *et al.*, "Agriculture, Forestry and Other Land Uses (AFOLU)," *Climate Change 2022 - Mitigation of Climate Change*, pp. 747–860, Aug. 2023, doi: 10.1017/9781009157926.009.

[15] "Pathways towards lower emissions," *Pathways towards lower emissions*, Dec. 2023, doi: 10.4060/CC9029EN.

[16] "Costs in large-scale forestry - Skogsstyrelsen." Accessed: Sep. 22, 2025. [Online]. Available: https://www.skogsstyrelsen.se/en/statistics/economy/costs-in-large-scale-forestry/