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Review

Assessing a bio-energy system with carbon capture and storage (BECCS) through dynamic life cycle assessment and land-water-energy nexus

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ABSTRACT

Nowadays, much attention is being paid to so-called Negative Emissions Technologies (NETs), designed to remove carbon dioxide from the atmosphere and keep global temperature rise below 1.5 °C. The deployment of NETs can trigger environmental impacts, which can be addressed through the lens of Life Cycle Assessment (LCA). According to the literature, there are several drawbacks when NETs are assessed under the life cycle framework. In this sense, this study aims at contributing to the literature by assessing a NET in a manner that the existing drawbacks are overcome. For such purpose, dynamic LCA and land-water-energy nexus were applied to a Bioenergy with Carbon Capture and Storage system (BECCS). The results show that harnessing residual forest biomass for electricity generation and carbon storage accomplished a great positive climate performance. In line with European climate goals, climate change impact resulted in −2.49E+04 kg CO_{2eq}/MWh_e and −3.40E+04 kg CO_{2eq}/t C_{stored} at year 20. However, the BECCS system analyzed comes at the expense of impacting land, water and energy that cannot be overlooked. The land impact was 3.57E+05Pt/t C_{stored} and 2.61 E+05Pt/MWh_e, green water impact was 11.1 m^3/t C_{stored} and 8.16 m^3/MWh_e, and the Energy Return on Energy Investment (EROI) was 3.34. The sensitive analysis indicates that special attention should be paid to the efficiency of the system since it directly impacts on land, water and energy (EROI). Finally, this study contributes to increasing the knowledge on NETs, thus supporting climate-energy policymaking.

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) special report on climate change [1], all pathways to limit global temperature increases to 1.5 °C rely on the removal of carbon dioxide (CO_2) by means of different technologies. However, the deployment of Carbon Dioxide Removal (CDR) technologies, also known as Negative Emissions Technologies (NETs), raises concerns not only due to the reliability and feasibility of capturing and storing carbon (C) but also to their environmental side effects. In this sense, Life Cycle Assessment (LCA) can be a valuable methodology to comprehensively reflect the main environmental issues of NETs. Currently, many studies have assessed the environmental impacts of NET through LCA, where greater attention is paid to the impact on climate change [2–5].

The characteristics of NETs are very diverse, which entails disparity between systems, even among the same type of NET. This, in turn, leads to various technical and methodological differences (e.g., input application, resource and energy production, the C capture and storage system, boundaries, functional unit, etc.). Consequently, the LCA results obtained can range widely with differences owing to these choices. In this context, several authors have exposed the main issues and drawbacks in regard to C accounting and LCA of NETs [6–9]. Tanzer & Ramirez (2019) exposed the inconsistencies in the accounting of emissions (e.g., indirect land use, avoided emissions, etc.), while Brander et al. (2021) remarked on the lack of understanding of C accounting and the different accounting challenges [6,8]. On the other hand, Terlouw et al. (2021) highlighted that LCA is often applied in inconsistent, misleading, and ambiguous ways [9]. These authors also provided a

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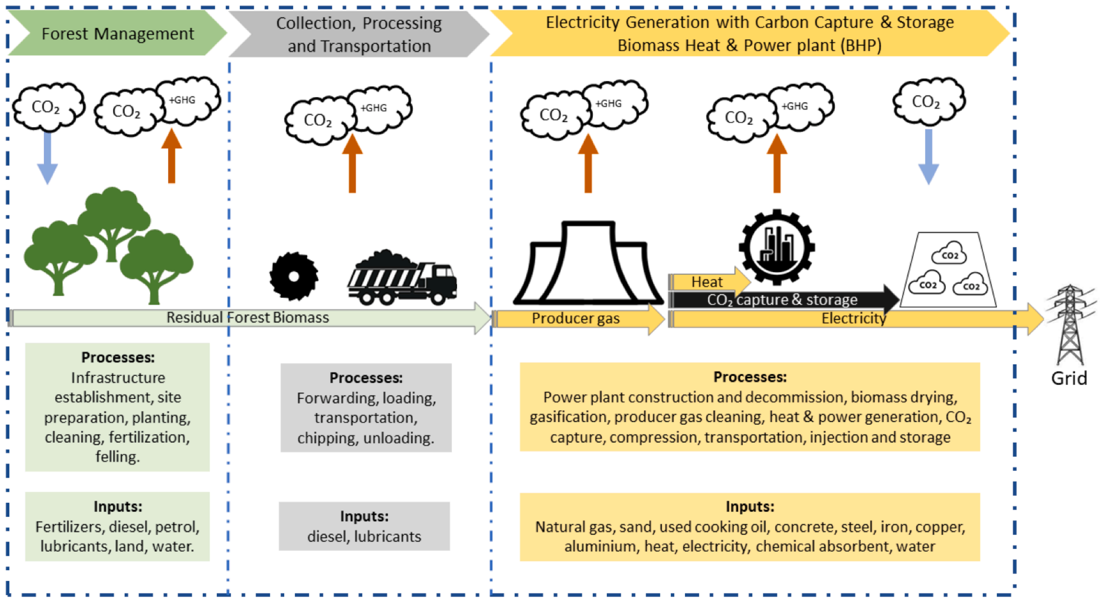

Fig. 1. System boundaries of the Biomass Heat and Power Plant with Carbon Capture and Storage.

perspective on how to conduct future LCA studies of CDR technologies in a consistent way, thus avoiding common mistakes. This was in agreement with previous work made by other authors [7,10,11].

From the LCA studies of Bioenergy with Carbon Capture and Storage (BECCS) found in the literature, important inconsistencies and drawbacks can be highlighted [7,9]. Firstly, BECCS is a multi-purpose system that provides both energy and C storage, but C storage is not considered in the functional unit (FU), which only reflects energy production, being 1 kWh, or MWh, or MJ the most applied (e.g., [2,12,13]). This then hampers comparison with other NETs. Besides, most of the life cycle inventories are not transparent and clear which indicates the need for a more detailed specification of inputs and outputs. More importantly, both C accounting and climate change impact are presented misleadingly. In this sense, several points can be highlighted:

a) C storage is mixed with C emissions abatement and reduction in the same accounting [14–16];
b) C accounting and storage are not clearly stated in quantitative terms, e.g., [17–20];
c) C storage is represented in terms of climate change impact which is quantitatively misleading [3,21];
d) so far, only static LCA has been applied to assess climate change impact, revealing inconsistency since the climate is a dynamic system [9,22]; and.
e) the accounting of greenhouse gas (GHG) emissions is limited mainly to carbon dioxide (CO_2) and methane (CH_4) with exceptions where nitrous oxide (N_2O) is additionally considered, excluding other GHG emissions [3,4].

Lastly, the consumption of resources such as land, water, energy and minerals are poorly considered in LCA studies of BECCS [9].

Bearing in mind the presented background, this study aims at bridging the existing gap and going behind the state-of-the-art by assessing a NET, following the recommendations previously made by several authors. This means that the NET system is assessed in a manner that its features match with methodological choices, overcoming this way the abovementioned drawbacks. For such purpose, the climate change impact of a BECCS system is evaluated through the lens of dynamic life cycle assessment (dLCA) and land-water-energy resources nexus. The electricity generation from direct gasification of residual forest biomass (RFB) produced by logging activities in Portugal was taken as a study case, based on Briones-Hidrovo et al. (2021) [23], to which the C capture and storage system was adapted.

Table 1
Data on the inputs for the forest management operations up to felling (with harvester) for 1 t (dry basis, db) of eucalyptus logging residues. Source: [25,24].

Inputs	Unit	Value
Diesel	l	3.639
Petrol	l	0.0714
Lubricants	l	0.1842
Superphosphate	g	721.8
Ternary fertilizer 1 (15 % N, 12 % P_2O_5, 9 % K_2O)	g	129.32
Ternary fertilizer 2 (15 % N, 8 % P_2O_5, 8 % K_2O)	g	2,847.4
N-based fertilizer	g	1,709.0
Water (green)	m^3	129.23
Land	ha	0.189

2. Materials and methods

2.1. Functional unit and system boundaries

LCA studies on BECCS commonly consider only the generation of energy in the FU (e.g., KWh [2,13]). However, BECCS are multi-functional systems since they also aim to capture and store C [9]. In this sense, two FUs were considered: 1 t C_{stored} and 1 MWh_e. This will allow future comparison with other NET [9].

A cradle-to-grave approach was applied, and the system boundaries comprise the following three stages: i) Forest Management (FM), ii) Collection, Processing, and Transportation (CPT) of forest biomass, and iii) Electricity Generation with Carbon Capture and Storage (EG-CCS) through a Biomass Heat & Power Plant (BHP-CCS) (Fig. 1). The whole system was analyzed for a lifespan of 25 years [23].

2.2. Life cycle inventory

2.2.1. Forest management stage

This stage includes the following processes as part of the eucalyptus forest's operations related to eucalyptus forest management: infrastructure establishment, site preparation, planting, cleaning, fertilization, selection of coppice stems and felling (Fig. 1). The main inputs of this stage are fertilizers, diesel, petrol, lubricants, land, and water

Table 2
Data on the inputs the operations undertaken during the collection and chipping of forest residues per 1 t (dry basis, db) of eucalyptus logging residues, based on [25].

Inputs	Unit	Forwarding Forwarder	Loading or unloading of loose residues	Chipping [a]	Loading of chips
Diesel	l	1.920	0.462	3.940	0.498
Lubricants	l	0.096	0.023	0.197	0.024

(Table 1). The inventory data other than land use and water were taken from Dias and Arroja (2012) [24] by applying allocation by mass for input partitioning between the outputs that leave the forest system. The allocation factors were: 75.3 % for wood, 10.3 % for bark, 10.0 % for logging residues and 4.4 % for stumps [25]. In addition, half of the logging residues and stumps were assumed to be left on the forest soil due to logistical, technical, and ecological constraints. In this sense, no environmental burdens were allocated to these residues since they are not an output of the forest system.

The amount of land use was determined based on eucalyptus logging residues' annual production and eucalyptus forest plantations' occupation area in Portugal [26,27]. Eucalyptus plantations are not irrigated and, thus, water consumption only includes green water (rainwater), which data come from Quinteiro et al. (2015) [28]. A mass allocation factor was also applied for both water consumption and land use. Except for land and water, the production processes of inputs and their air emissions (including GHG) were retrieved from the Ecoinvent database V3.7.1 [29]. These emissions can be seen in Appendix A, and the names of the Ecoinvent processes adopted can be consulted in the Supplementary Material.

2.2.2. Collection, processing, and transportation stage

This stage includes the forwarding, chipping, loading, unloading operations and transportation of residues from the forest up to the power plant. The total distance covered was 35 km. A more detailed description of processes and inventory data can be consulted in Dias (2014) [25]. The main inputs are diesel and lubricants (Table 2) for which data on production and transportation processes were taken from the Ecoinvent database V3.7.1 [29]. More details are presented in Supplementary Material.

2.2.3. Electricity generation with carbon capture and storage stage

Taking as reference the study of Briones-Hidrovo et al. (2021) [23], the power plant was upgraded to a BHP-CCS. The main technical characteristics of BHP-CCS are indicated in Table 3 while Figs. 2 and 3 show BHP-CCS and monoethanolamine (MEA)-based carbon capture system layout, respectively. BHP-CCS comprises the following processes: RFB drying, direct (air) gasification in fluidized bed reactor, producer gas (PG) cleaning, gas turbine (GT), and electricity generation; Heat Recovery Steam Generator (HRSG) and steam production; carbon capture, compression, transportation, injection, and storage. The average amounts of construction materials for BHP-CCS were taken from the literature [21,23], and its inventory can be seen in Supplementary Material.

The average moisture content of 40 %wt for the chipped RFB was considered [30]. After drying (until 11.8 %wt moisture), residues enter the fluidized-bed reactor where the raw producer gas (PG) is obtained. From the characteristics and parameters of the previous gasification study [23], the gasifier thermal efficiency (cold gas efficiency) and the C conversion efficiency were estimated at 70 % and 99 %, respectively, yielding 2.33 t PG/t RFB_{db} [19,31]. In addition, natural gas was used as the start-up fuel in the gasification process. The bottom and fly ashes and bottom bed (sand, ashes) waste generated during biomass gasification were disposed of at a sanitary landfill [23].

The PG is then cleaned through a multi-stage scrubber oil-based gas washer (OLGA) system [32,33]. It was assumed 0.1 % of CO_2 losses in the cleaning system. After cleaning, 55 % of PG mass flow is fed into the turbine gas system (Brayton cycle) of 7 MW_e. With a plant load factor of 90 %, the electrical efficiency of the system was 18.58 % (Table 3). It is worth noting that the electric consumption of carbon capture, compression and injection systems were considered part of the internal consumption of the power plant. The elemental and proximate analysis of RFB, PG properties and energy-mass balance of BHP-CCS can be

Table 3
Inventory, parameters, and characteristics of the BHP-CCS system.

Parameter	Unit	Value
Resources		
Type of biomass	–	Eucalyptus RFB
Biomass lower heating value[a]	MJ/kg	17.60
Biomass flow (db, 11.8 % moisture)	kg/s	3.221
Annual biomass consumption (db)	kt/year	91.42
Total clean producer gas mass flow	kg/s	7.511
Producer gas mass flow, gas turbine input	kg/s	4.110
Producer gas mass flow, HRSG input	kg/s	3.401
Producer gas lower heating value	MJ/kg	4.660
Biomass-electricity ratio	t RFB (db)/MWh_e	2.031[a]
Natural gas	Nm^3/MWh_e	3.000
Sand	kg/MWh_e	20.00
Used cooking oil	kg/MWh_e	8.120
Water consumption	m^3/MWh_e	1.000[b]
Power plant		
Gasifier thermal power	MW_{th}	50.00
Gasifier thermal efficiency	%	70.00[c]
Carbon conversion efficiency	%	99.00
Gas turbine efficiency	%	37.00
Electrical Efficiency	%	18.40
Installed power capacity	MW_e	7.000
Plant factor	%	90.00
Annual electricity generation	GWh_e/year	44.39
HRSG efficiency (with supplementary firing)	%	90.00
Steam mass flow (HRSG output)	kg/s	6.078
Carbon Capture and Storage[d]		
Carbon capture technology	–	Post-combustion, absorption
Sorbent type	–	Monoethanolamine
Capture efficiency	%	90.00
Monoethanolamine consumption	kg/t CO_2-captured	1.850
CO_2 mass flow (turbine outlet)	kg/s	4.666
Absorption rate	g CO_2/kg MEA	720.0[e]
Heat, capture process	MWh_{th}/t CO_2-captured	1.111
Electricity, capture process	kWh_e/t CO_2-captured	23.60
Electricity, CO_2 compression transportation, and injection	kWh_e/t CO_2-captured	19.71
Number of compressors	–	2.000
Compressors, mechanical efficiency	%	99.00
Compressors, isothermal efficiency	%	80.00
Compressors, total electric power	MW_e	0.334
Compressor 1, discharge pressure	MPa	11.00
Compressor 2, discharge pressure	MPa	15.00
CO_2 compressor leakage	t CO_2/MW_e/year	23.20
Total transportation distance	km	70.00
Type of storage	–	Saline aquifer
Location reference	–	Coimbra, Portugal[f]
Reservoir capacity	Mt	352.0[f]
Number of wells	–	1.000
CO_2 injection rate	t CO_2/day	362.8
CO_2 pipeline leakage	t CO_2/km/year	2.320

[a] [31]; [b] blue water consumption based on Jin et al. (2019); [c] gasification at 11.8 % moisture based on experimental laboratory data [31]; [d] Data taken from [34] unless otherwise specified; [e] [44]; [f] [45].

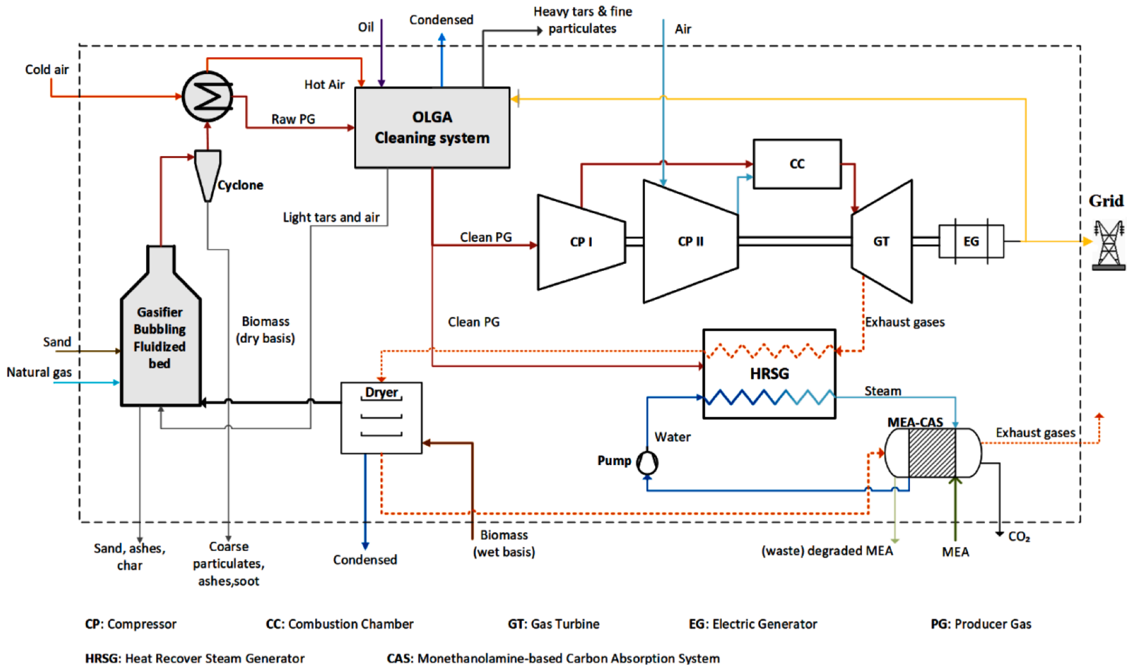

Fig. 2. Biomass Heat & Power Plant with Carbon Capture and Storage layout.

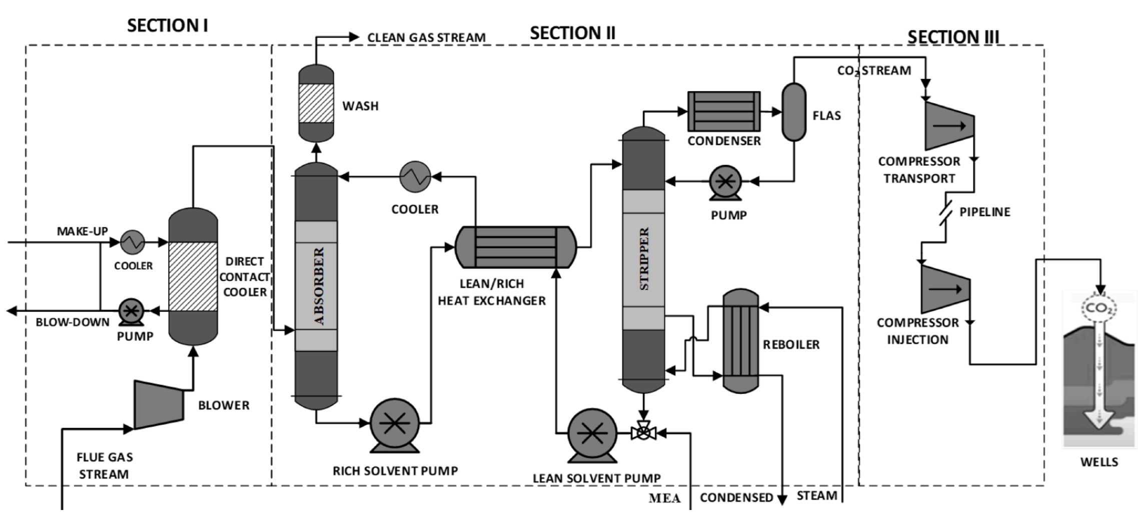

Fig. 3. Schematic diagram of the MEA-based Carbon Capture system.

consulted in Supplementary Material.

Regarding the CCS system, post-combustion with absorption through MEA sorbent was considered, with a capture efficiency of 90 % [34,35]. The C to be captured is biogenic, with a CO_2 mass flow of 4.66 kg/s at the gas turbine outlet, based on stoichiometric combustion (Table 3). For the capture process, it was considered an average MEA consumption rate of 1.85 kg/t $CO_{2\text{-captured}}$ [2,34,36–43]. Steam was used to supply heat for the stripper in the MEA unit. Both gas turbine exhaust gases and the combustion of 45 % PG mass flow were used to generate steam through the heat recovery steam generator (HRSG) with a supplementary combustion unit for PG. Heat and electricity demand ratios were taken from the literature (Table 3).

After capturing, CO_2 is compressed to 11 MPa and transported to the storage site, a saline aquifer located 70 km away from the power plant facility. The injection rate was estimated at 15.12 t CO_2/h, at 15 MPa. Both compressor and pipeline CO_2 leakage were included in the C and climate impact accounting. Details of the calculation of the CCS process are presented in Supplementary Material. The CO_2 emissions from plant decommissioning, uncaptured CO_2, and CO_2 leakage (CO_2 compression and pipeline) were estimated based on ratios found in the literature (Table 3). The gas emissions (including GHG) of the BHP-CCS construction and operation, and MEA production were retrieved from Ecoinvent database V3.7.1 [29] and are presented in Appendix A (Table A1 and A2).

2.3. Environmental impact assessment

2.3.1. Carbon and climate impact accounting and balance

The life cycle C accounting and balance was carried out in C units, using a mass-weight ratio based on molar mass for unit conversion. The emissions considered are CO_2, CH_4, and CO (Table A2). Hence, the sum of life cycle C emissions (C_e, t C) during the lifespan of the power plant (25 years) and throughout all the stages (FM, CPT, EG-CCS) was determined as:

$$C_e^{25yr} = \sum_0^{25yr} C_{CO_2} + C_{CH_4} + C_{CO} \tag{1}$$

The total amount of C to be captured (C_c, t C) was determined based on the life cycle CO_2 emissions from the gas turbine (Gt_{CO2}, t C) and carbon capture efficiency (E_{CC}, %) of the system (Table 3) during the lifespan (25 years), as follows:

$$C_c^{25yr} = Gt_{CO_2} \times E_{cc} \tag{2}$$

Then, the life cycle C balance for the lifespan, including all the stages (FM, CPT, EG-CCS) was:

$$C_{balance}^{25yr} = C_e^{25yr} - C_c^{25yr} \tag{3}$$

A negative result indicates that more C is being withdrawn than emitted and hence denoted as negative emissions. It is worth noting that the C captured at the outlet of the gas turbine is the one that has been previously sequestrated during forest growth. To know the net C storage (C_s, t C), the following equation was applied:

$$C_s^{25yr} = \sum_0^{25yr} C_c - C_L \tag{4}$$

where C_L represents life cycle C emissions losses due to compressors and pipeline leakages (t C). The life cycle C accounting and balance was modelled through an excel spreadsheet. Regarding climate change impact, the dynamic life cycle assessment (dLCA) approach was applied. This approach considers time-dependent characterization factors and a dynamic life cycle inventory (dLCI) which means a temporal distribution of the GHG emissions along a determined time horizon. In this sense, the dynamic characterization factor (DCF, W m^{-2} kg^{-1}) for any year after the emission of a GHG proposed by Levasseur et al. (2010) was applied [22]:

$$DCFi(t) = \int_{t-1}^{t} a_i \times [C_i(t)]dt \tag{5}$$

where a is the instantaneous radiative forcing per unit of mass increase in the atmosphere, C(t) is the time-dependent atmospheric load of the released GHG, and i is the released GHG. The DYNCO2 tool (excel spreadsheet, version 2.0) developed by Levasseur et al. (2010) was used to calculate the impact of GHG emissions over the set period. The life cycle of the system under analysis was divided into yearly steps with the corresponding amount of GHG emissions. The quantities of GHG emitted alongside processes within the 3 stages were obtained from Ecoinvent database V.3.7.1 [29] and introduced in DYNCO2 tool. GHG emissions inventory can be seen in Appendix A (Table A1). As result, the DYNCO2 tool returns the relative impact (GWI_{rel}, kg $CO_{2\text{-eq}}$) that is calculated as follows [22]:

$$GWI(t)_{inst} = \sum_i \sum_{j=0}^{t} [g(i)]_j \times [DCF_i]_{t-j} \tag{6}$$

$$GWI(t)_{cum} = \sum_{j=0}^{t} GWI(j)_{inst} \tag{7}$$

$$GWI(t)_{rel} = \frac{GWI(TH)_{cum}}{\int_0^{TH} a_{CO_2} \times C_{CO_2}(t)dt} \tag{8}$$

Being GWI_{inst} the radiative forcing caused by the life cycle GHG emissions at any specific time along the life cycle under analysis; GWI_{cum}, the sum of the instantaneous impacts from time zero to a specific time, and GWI_{rel}, the ratio of the life cycle cumulative impact on global warming over the cumulative impact of a 1 kg CO_2 pulse emission at time zero and expressed in kg CO_{2eq}; $[g(i)]_j$ the dynamic inventory result for GHG i at time j, and TH is the time horizon over which the calculation is considered. It is worth highlighting that year 1 included emissions of power plant construction while year 25 included the emissions of power plant decommissioning. For a better overview of the climate change impact results, they were presented in a time horizon of 500 years. In particular, the results were highlighted for years 20, 80, and 100. This goes hand-in-hand with the European Union GHG emissions reduction plan up to 2050, the time horizon of the climate change scenarios set by the IPCC, and the GWP for 100 years' time horizon impact, which is the most commonly used in the literature. This way, it will be shown the climate change impact in the years 2040, 2100, and 2120.

Table 4
The indicators and characterization factors addressed in LANCA method. Source: [47].

Indicator	Land use activity	Characterization factor, CF	CF unit
Erosion resistance (ER)	Occupation/ transformation	Erosion potential	kg soil loss/(m^2. year)
Mechanical filtration (MF)		Infiltration Reduction Potential	m^3 water/(m^2. year)
Physicochemical filtration (PCF)		Filtration Reduction Potential	mol reduction potential/(m^2)
Groundwater regeneration (GWR)		Groundwater Regeneration Reduction Potential	m^3 groundwater/ (m^2.year)
Biotic production (BP)		Biotic Production Loss Potential	kg biotic production/(m^2. year)

2.3.2. Land-Water-Energy nexus

- *Land use impact*

The impact on land use was assessed with the Land Use Indicator Value Calculation (LANCA) method and modelled through an excel spreadsheet. The LANCA method takes part of the environmental footprint method proposed by the European Commission [46] and assesses the land-use impact at the midpoint level based on five soil functions and indicators: erosion resistance, mechanical filtration, physicochemical filtration, groundwater regeneration, and biotic production [47] (Table 4). The given characterization factors (CF) are calculated in terms of land occupation for specific land-use type at a country level [47,48]. It should be noted that the CF values of land occupation and transformation are identical since LANCA method makes no distinction between them [47]. In this sense, the set of land use impacts (LU_i) was calculated as follows:

$$LU_i = CF_{occ,j,x,i} \times A_{occ,FU} \tag{9}$$

where CF is the characterization factor for occupation (occ) of a specific land use type (j) in a given country (x), for the impact category (i) (e.g., erosion resistance), and A is the area of occupation for a given set of time in respect to the FU, expressed in m^2 a. The updated CFs presented by de Laurentiis et al. (2019) were applied [48] (see Supplementary Material).

Lastly, the LANCA method provides an aggregated index called Soil Quality Index (SQI) that is built based on the set group of indicators: erosion resistance (ER), groundwater regeneration (GWR), mechanical filtration (MF), and biotic production (BP). This single score index, expressed in Points (Pt), allows simplifying the interpretations of midpoint impact results, providing this way with a measure of soil impact of different land-use interventions. Bearing in mind that the higher the values, the larger the impacts, SQI was determined based on aggregated occupation characterization factor ($CF_{occ,agg}$) at a country level, equal to 67.3Pt/m^2*year [48]:

$$SQI = CF_{occ,agg} \times A_{occ,FU} \tag{10}$$

- *Water impact*

Table 5
Life cycle C accounting results per stage, per year and for the set lifespan of the system.

Stage		t C/year	t C/25 years
FM		5.65E+02	1.41E+04
CPT		8.63E+02	2.16E+04
EG-CCS	Operation	2.06E+02	5.15E+03
	Construction materials (year 1)	3.62E+02	3.62E+02
	Decommissioning (year 25)	5.22E+00	5.22E+00
	CCS system (MEA production, uncaptured CO_2, and CO_2 leakage)	3.80E+03	9.51E+04
	C capture	−3.25E+04	−8.14E+05

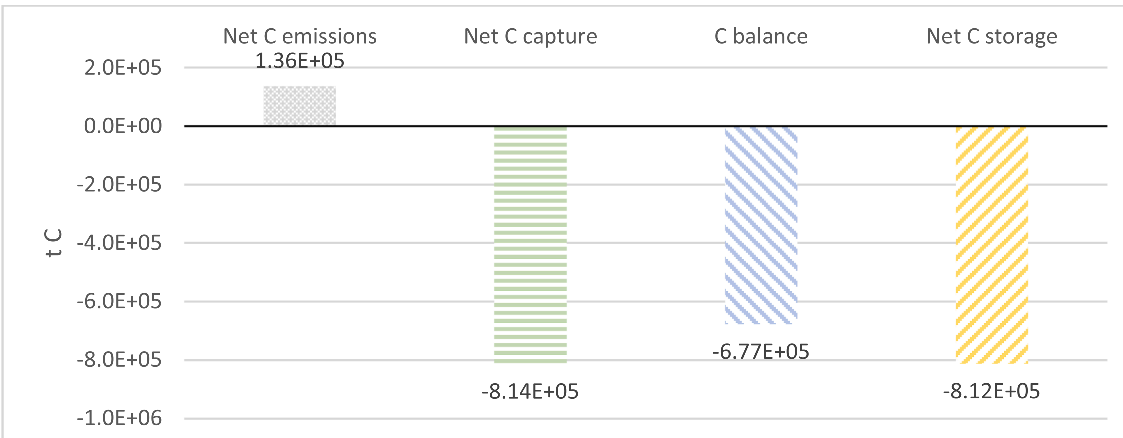

Fig. 4. Life cycle carbon balance during the lifespan of the system.

Common water life cycle impact methods account for blue water use and consumption [49,50]. However, less attention has been paid to green water and its flows [28]. It is well-known that several crops use mainly green water for biomass growth which turns out to be the main life cycle water consumption of many bioenergy systems [51,52]. In this context, Quinteiro et al. (2015) assessed the impacts on terrestrial green water flows (TGWI, m^3/ha year) and reductions in surface blue water production (RBWP, m^3/ha year) of *Eucalyptus-globulus* forest in Portugal [28]. Hence, the water impact of the BHP-CCS system was determined as follows[1]:

$$Wi = \frac{i_{TGWI,RBWP} * A}{P_{FU}} \tag{11}$$

where Wi is the water impact per FU (m^3/MWh_e; m^3/t C_{stored}), i is either the TGWI or RBWP impact in m^3/ha.year, A is the total allocated land required to produce residues forest, in ha, and P_{FU} is either the annual electricity generation (MWh_e/year) or annual C storage (t C_{stored}/year). The water impact was modelled through an excel spreadsheet.

- *Energy Return On Energy Invested (EROI)*

The Energy Return on Investment (EROI) is a means of measuring the quality of various fuels by calculating the ratio (dimensionless) between the energy delivered by a particular fuel to society and the energy invested in the capture and delivery of this energy [53]:

$$EROI = \frac{E_{out}}{E_{in}} \tag{12}$$

where E_{out} is the total energy delivered to society and E_{in} is the total energy invested in the capture and delivery of E_{out} [53], both in MJ. E_{in} was determined by the sum of direct and indirect energy consumed by the processes along the stages of FM, CPT, and EG-CCS:

$$E_{in} = E_{FM} + E_{CPT} + E_{EG-CCS} \tag{13}$$

where E_{FM}, E_{CPT} and $E_{EG\text{-}CCS}$ are the energy consumed in FM, CPT and EG-CCS stages, respectively. It is worth highlighting that E_{in} was proportionally allocated according to the PG mass flow used for electricity generation. Energy input was estimated based on the Ecoinvent database V3.7.1, while the accounting was performed through an excel spreadsheet. Detailed energy accounting is shown in Supplementary Material.

2.4. Assumptions and limitations

Some aspects of carbon accounting, climate change impact and land-water-energy nexus assessment should be kept in mind. Firstly, only CO_2 emissions were accounted for in the plant decommissioning. Furthermore, CH_4 emissions and/or uptake from the forest were excluded due to the high uncertainty [54] and the lack of local studies. Secondly, the DYNCO2 tool (version 2.0) is based on the IPCC 5th Assessment Report from 2014. This means that GWP and GTP values have been calculated based on constant background atmosphere concentrations of 391 ppm CO_2 [55,56]. Currently, CO_2 atmospheric concentration is 417 ppm, according to NASA.[2] Moreover, no distinction was made between biogenic and fossil CO_2 emissions.

Thirdly, the blue water consumption of BHP-CCS was considered negligible since it represented only 0.1 % of total water consumption. Therefore, only green water was accounted for. Fourthly, for the application of the LANCA method, the CFs chosen refers to the land use type of *forest, used*. This choice is based on the characteristics of the land under analysis. In addition, indirect land use was not considered since eucalyptus forest plantations are assumed to have not displaced any other human activity that had entailed new land use. Lastly, the energy consumption of plant decommissioning was considered negligible due to

[1] Quasi-natural forest as reference land use.

[2] https://climate.nasa.gov/.

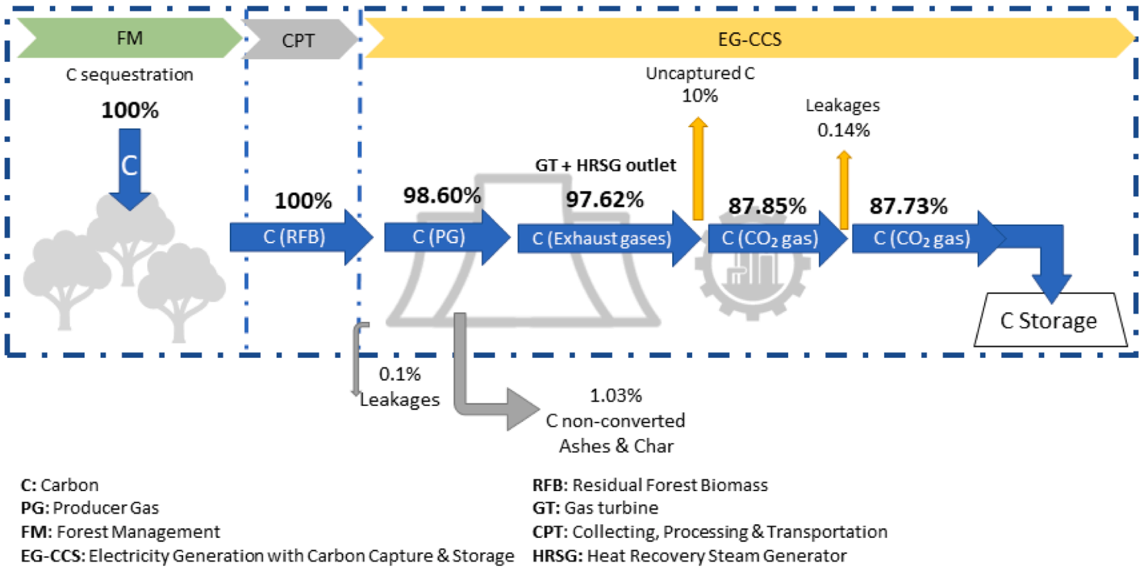

Fig. 5. Life cycle carbon input fluxes within stages, shown in percentage.

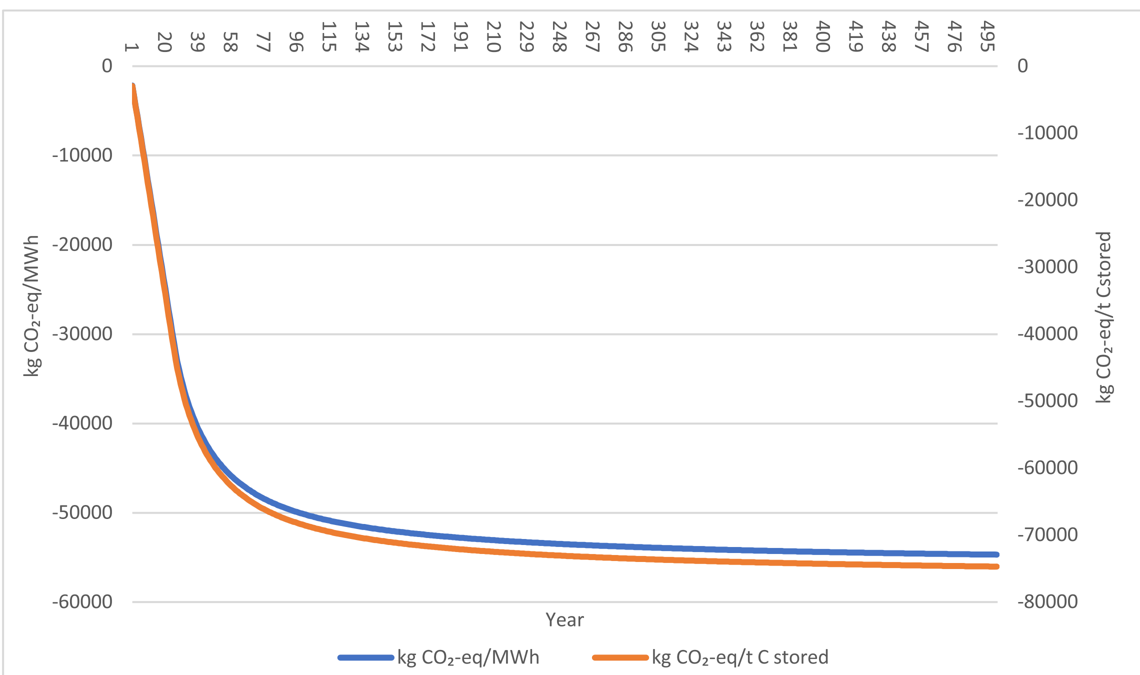

Fig. 6. Relative Global Warming impact results per FU over time.

its very low value.

3. Results

3.1. Carbon emissions accounting and balance

The accounting and balance of life cycle C emissions, capture and storage are presented in Table 5 and Fig. 4. Fig. 5 shows the breakdown of carbon input fluxes within the boundaries of the system for the set lifespan. The results per FU obtained were 0.17 t $C_{emitted}$/t C_{stored}, 1.37 MWh_e/t C_{stored} (or 0.73 t C_{stored}/MWh_e) and 0.12 t $C_{emitted}$/MWh_e. Total net life cycle C emissions over the 25 years resulted in 1.36E+05 t C. The FM stage and the CCS system within the EG-CCS stage were the major sources of C emissions. Total net life cycle C capture over the 25 years resulted in −8.14E+05 t C, giving place to a life cycle C balance of −6.77E+05 t C for the set lifespan. On the other hand, the life cycle C storage was slightly lower than the total life cycle C capture due to the emission of 4.63E+01 t C/year from compressors and pipeline leakages. This way, 87.73 % of the total C input was stored (Fig. 5).

3.2. Climate change impact

From year 1, the relative global warming impact (GWI_{rel}) of the BHP-CCS was negative (Fig. 6) that turns it into an effective decarbonization technology. In this sense, it was obtained a climate change impact of −2.49E+04 kg CO_{2eq}/MWh_e, −4.87E+04 kg CO_{2eq}/MWh_e, −5.02E+04 kg CO_{2eq}/MWh_e, and −3.40E+04 kg CO_{2eq}/t C_{stored}, −6.65E+04 kg CO_{2eq}/t C_{stored}, −6.85E+04 kg CO_{2eq}/t C_{stored}, at years 20, 80 and 100,

Table 6
Land, water, and energy nexus per FU.

Parameter		Unit	Functional unit	
			1 t C_{stored}	1 MWh_e
Wi	TGWI	m^3	1.11E+01	8.16E+00
	RBWP		3.56E+02	2.61E+02
LU_i	ER	kg	6.08E+01	4.45E+01
	MF	m^3	3.39E+05	2.48E+05
	PCF	mol*year	4.68E+04	3.43E+04
	GWR	m^3	−6.35E+01	−4.65E+01
	BP	kg	3.55E+03	2.60E+03
	SQI	*Pt*	*3.57E+05*	*2.61E+05*
Energy	EROI	–	n/a	3.34E+00
	Required	MJ	5.67E+03	n/a

respectively. After year 100, the climate impact tends to slightly stabilize, achieving this way the greatest climate impact mitigation (Fig. 6).

3.3. Land-water-energy nexus

The accounting and impact assessment of land, water and energy (EROI) are presented in Table 6. The Wi related with TGWI resulted in 11.1 m^3/t C_{stored} and 8.16 m^3/MWh_e, whereas the Wi related with RBWP resulted in 356.1 m^3/t C_{stored} and 260.7 m^3/MWh_e. Regarding LU_i, 0.39 ha were needed to generate 1 MWh_e and 0.53 ha to store 1 t C. The SQI resulted in 3.57E+05Pt/t C_{stored} and 2.61E+05Pt/MWh_e. It is worth noting that GWR resulted negative, which might suggest an improvement. This is later addressed and discussed in the Discussion section. Lastly, the net energy required for the storage of 1 t C was equal to 5.67E+03 MJ while the net energy input (E_{in}) for the generation of 1 MWh_e was equal to 1.08E+03 MJ, originating an EROI of 3.34.

3.4. Sensitivity analysis

One key element of energy systems is their efficiency. That said, the results of the BHP-CCS with lower gasifier thermal efficiency than in the base scenario (70 %) were analyzed. Thus, two scenarios were considered: 60 % (G1) and 50 % (G2). These values are based on earlier studies and fall within the gasifier thermal efficiency typical range (cold gas efficiency) [23,31]. A scenario with higher efficiency was not considered since most common efficiency values are found below 70 % [23,31]. Moreover, both technology and the type of biomass resource affect the efficiency of the gasifier [19]. The results are presented in Fig. 7 per 1 MWh_e and 1 t C_{stored}. Other possible variables such as the logistics in the biomass supply chain (transportation) and carbon capture efficiency were not considered in the analysis because they are not as critical and sensitive as the gasifier thermal efficiency.

Both C storage and electricity generation decreased by 14 % in the G1 scenario while they decreased by 29 % and 36 % in the G2 scenario, respectively. The difference in the percentage of variation is due to the C conversion efficiency of the gasifier which in turn implies capturing and storing less C. The climate change impact (GWP_{100} expressed as kg $CO_{2\text{-}eq}$ per MWh_e) remains practically the same in the G1 scenario. However, it decreased by 12 % in the G2 scenario. In terms of resources, the lower the gasifier thermal efficiency, the greater the impacts on land, water, and energy (EROI). In the G1 scenario, land and water impacts increased 17 %, while in the G2 scenario, these impacts increased 40 %. Lastly, the EROI worsened as gasifier thermal efficiency decreased, falling to 2.62 in the G2 scenario, a reduction of 21 % (Fig. 7).

4. Discussion

According to results, CO_2 played a major role than other GHG in both life cycle C accounting and climate change impact. CO_2 and CO represented 92 % and 8 % of total life cycle C accounting, respectively, while CH_4 had a negligible impact. The main source of CO_2 emissions was the uncaptured CO_2, while the use of diesel and lubricants associated with forest activities were the main sources of CO. Furthermore, CO emissions were what ultimately made the difference between life cycle C balance and storage. Anyway, every case study should be carefully analyzed since the amount of CH_4, CO and other GHGs could vary due to differences in biomass resource production, applied technology, and final product output [5,57]. Indeed, many GHGs have a shorter lifetime compared to CO_2. This means that a shorter time horizon will allow to

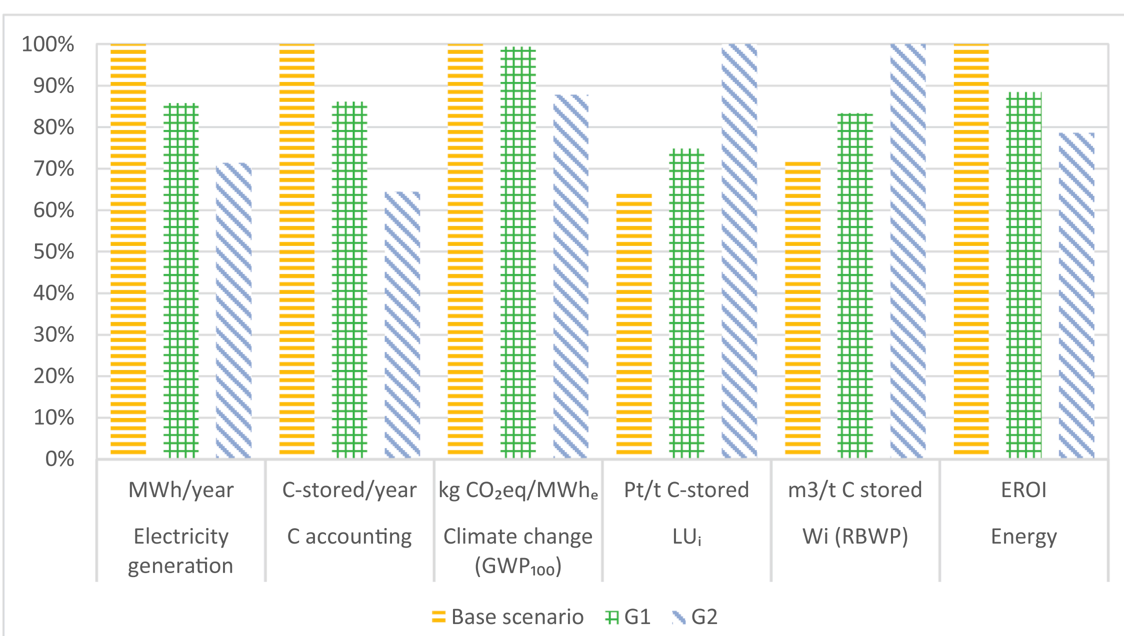

Fig. 7. Sensitive analysis results of carbon accounting, climate change and land-water-energy nexus (considering 100% for the scenario with the best performance or largest impact).

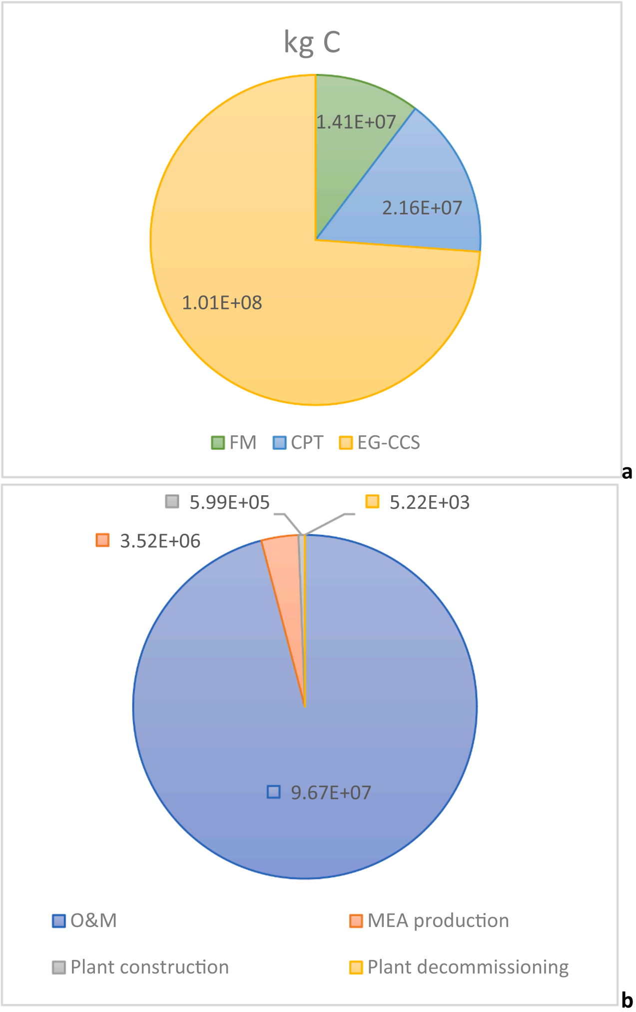

Fig. 8. Life cycle C emissions a) per stage and b) breakdown of EG-CCS stage.

know the impacts closer in time [58].

The EG-CCS stage was the main source of C emissions, accounting for 74 % of total C emissions, followed by FM (16 %) and CPT (10 %) stages, respectively (Fig. 8a). Within the EG-CCS stage, the operation and maintenance (O&M) of the plant had the highest share of C emissions, being likewise the uncaptured CO_2 the major source. Plant construction, decommissioning, and CO_2 leakage had a negligible impact (Fig. 8b). On the other hand, CO_2 was likewise crucial in climate change impact since it largely outweighed other GHG emissions in quantitative terms. GHG emissions other than CO_2 had a climate change impact significantly lower, representing 1 % of the total impact.

In terms of resource impact, a point to highlight is the relation between LU_i and Wi results. Land use alters soil conditions that in turn entails the potential loss of topsoil, vegetation, and water retention capacity, as well as the overall alteration of green water flows. Those changes are reflected in the LU_i categories results (Table 6), except for the GWR indicator which is reduced in eucalyptus forest plantations. This result of GWR is inconsistent with the study of Quinteiro et al. (2015) [28], which considers that green water consumption by eucalyptus for biomass growth translates into an increase in evapotranspiration, less water infiltrated and the decrease of replenishment of groundwater (GWR), all at once. A possible reason for this discrepancy is that the CF of LANCA method is generic, whereas the study of Quinteiro et al. (2015) [28] is site-specific and hence, their results are more accurate. This means that SQI results may be underestimated. LANCA results should be taken with caution due to the lack of accuracy and it is suggested to use site-specific studies when possible.

Still, in the context of water consumption and impact, one cannot overlook the future climate consequences and the overall resources trade-offs of BECCS [59]. As noted by the IPCC, the deployment of afforestation for bioenergy and carbon capture and storage purposes as a land-based mitigation measure, if poorly implemented, can compound climate related risks to biodiversity, water supply, and food security, especially at large scales and in regions with constrained water resources and insecure land tenure [60]. According to the set scenarios and under the current GHG emissions trend, climate change is likely to decrease rainfall, soil moisture content, and exacerbate droughts in Portugal. As a matter of fact, half of the country will likely turn into desert land [61]. This will therefore have severe effects on forest and biomass resources, risking this way the feasibility of carbon sequestration and storage. That said, the determined water impact in this study will be magnified in the near future. Consequently, a radical shift in land management is urgently needed, seeking ecosystems' protection and restoration while adapting and coupling to the best available CCS technologies.

In regard to EROI, the main energy input was diesel (79 %) used in both FM and CPT stages. In the EG-CCS stage, the CCS system had a remarkable impact on electricity generation since it demanded 9 % of the net annual electricity generation which therefore lowered the EROI.

BECCS-LCA studies are still scarce in the literature as noted by Terlouw et al. (2021) [9]. Table 7 compiles BECCS-LCA studies found with main features such as type of LCA, FU, C storage, climate change impact and resources accounting and impact (land, water, energy). Only LCA-BECCS studies with clear functional unit and system boundaries were considered. This way, it is showed how the different sets of features presented in Table 7 differ widely which in turn highlights limitations and drawbacks as indicated in previous studies [7,9]. It should be noted that LCA results usually vary due to differences in key parameters such as biomass type, FU, efficiencies, life cycle boundaries and impact assessment method [23]. Therefore, any comparison between LCA studies should be conducted with caution.

Some studies only addressed C accounting and climate change impact was not assessed [2,13,62]. These studies included fossil fuels such as coal and natural gas, and only considered non-biogenic CO_2. The remaining 16 studies presented C storage in terms of climate change impact. Most of the BECCS-LCA studies applied a cradle-to-grave approach and only 3 adopted a cradle-to-gate approach. Schakel et al. (2014) obtained a carbon storage range of −85–81 kg CO_2/MWh_e [2] while Yi et al. (2018) obtained −817 kg CO_2/MWh_e [13], being both far lower than the BHP-CCS system here analyzed (−2687 kg CO_2/MWh_e). Particularly, it was found in recent studies that either mixed emissions reduction with C storage or missed a proper and complete life cycle emissions inventory and balance [63,64]. Quantitatively speaking, C accounting results are highly relevant since they help to identify the best C capture and storage alternative.

Regarding climate change impact, only 9 BECCS-LCA studies presented a FU based on the output of electric energy (e.g., MJ_e, KWh_e, MWh_e). Those studies limited the GHG emissions accounting to CO_2, N_2O and CH_4, and carried out static LCA (GWP_{100} time horizon) obtaining a climate-positive performance with some exceptions [63,65]. That said, values from literature went from −2,000 to −500 kg CO_{2eq}/MWh_e [3,12,17,21,65–68] (Table 7). The climate change impact of this study (BHP-CCS) at year 100 was as high as −50,155 kg CO_{2eq}/MWh_e (Fig. 4). The large difference may be due not only to the differences between systems but also to the dynamic approach addressed. Quantitatively speaking, climate change impact result differs significantly when either a static or a dynamic approach is applied. Because GWP is highly sensitive to time horizon, the CF decreases with a fixed and long-time horizon (GWP_{100} time horizon) in the case of static LCA. Conversely, the CF increases in the dynamic LCA due to the shorter time horizon [22,69]. It is worth highlighting that three studies did not achieve negative climate change impact results in some scenarios addressed meaning that the systems under analysis could not be called a

Table 7
Literature review on BECCS-LCA studies.

Life Cycle Assessment								Resources Impact		
Study	Type LCA	Approach	FU	Resource	C storage/FU	Gases emissions included	Climate change impact/FU	Land	Water	EROI
[12]	Static	Cradle-to-Grave	1 MJ_e	Biomass	ND	CO_2	−0.165 kg $CO_{2\text{-eq}}$ (GWP_{100})	No	No	No
[2]	Static	Cradle-to-Grave	1 kWh_e	Coal, biomass	−85 to −81 g CO_2	CO_2	Unspecified	Yes	Yes	No
[76]	Static	Cradle-to-Gate	1 kg hydrogen	Biomass	ND	CO_2	−14.63 kg $CO_{2\text{-eq}}$ (GWP_{100})	Yes	No	No
[74]	Static	Cradle-to-Gate	1 t algae produced	Biomass	ND	CO_2	−5210 kg $CO_{2\text{-eq}}$ (GWP_{100})	No	Yes	Yes
[13]	Static	Cradle-to-Grave	1 MWh_e	Coal, biomass	−877 kg CO_2	CO_2	–	No	No	No
[62]	Static	Cradle-to-Grave	–	Natural gas, biomass	−1000 to −1 kg CO_2	CO_2	–	No	No	No
[3]	Static	Cradle-to-Grave	1 MWh_e	Coal, biomass	ND	CO_2, CH_4, N_2O	−876.6 kg $CO_{2\text{-eq}}$ (GWP_{100})	No	No	No
[17]	Static	Cradle-to-Grave	1 kWh_e	Biomass	ND	CO_2	−2 to −0.5 kg $CO_{2\text{-eq}}$ (GWP_{100})	No	No	Yes
[4]	Static	Cradle-to-Grave	1 GWh (fuel, heat)	Municipal solid waste, biomass, coal	ND	CO_2, CH_4, N_2O	−20 to −10 M Mg $CO_{2\text{-eq}}$ (GWP_{100})	No	No	No
[21]	Static	Cradle-to-Grave	1 MWh_e	Biomass	ND	Not specified	−874 to −665 kg $CO_{2\text{-eq}}$ (GWP_{100})	No	No	Yes
[5]	Static	Cradle-to-Grave	1 km	Biomass	ND	CO_2, CH_4	−0.02 kg $CO_{2\text{-eq}}$ (GWP_{100})	Yes	Yes	No
[75]	Static	Cradle-to-Grave	1 Mt biomass	Biomass	ND	Not specified	−1 to −1.500 kg $CO_{2\text{-eq}}$ (GWP_{100})	No	No	Yes
[57]	Static	Cradle-to-Gate	1 MJ hydrogen	Biowaste	ND	CO_2, CH_4	−0.02 to – 0.12 kg $CO_{2\text{-eq}}$ (GWP_{100})	Yes	No	No
[67]	Static	Cradle-to-Grave	1 MWh_e	Biomass	ND	CO_2, CH_4, N_2O[1]	−1131 to – 647 kg $CO_{2\text{-eq}}$ (GWP_{100})	No	No	No
[68]	Static	Cradle-to-Grave	1 kWh_e	Coal, natural gas, biomass	ND	CO_2	−1.63 to 0.30 kg $CO_{2\text{-eq}}$ (GWP_{100})	No[2]	No[2]	Yes
[65]	Static	Cradle-to-Grave	1 MWh[3]	Biomass	ND	CO_2	−859 to 743 kg $CO_{2\text{-eq}}$ (GWP_{100})	No	No	No
[63]	Static	Cradle-to-Grave	1 kWh	Biomass, oil	ND	CO_2	0.27 to 1.13	No	No	Yes
[64]	Static	Cradle-to-Grave	1 km	Biomass	ND	CO_2	-[4]	Yes	Yes	No
[66]	Static	Cradle-to-Gate	1 MJ jet fuel	Biomass	ND	CO_2	−127.1 to −121.8 g $CO_{2\text{-eq}}$ (GWP_{100})	Yes	Yes	No
This study	Dynamic	Cradle-to-Grave	1 MWh_e	Biomass	−0.73 t C_{stored} (-2.69 $CO_{2\text{-stored}}$)	CO_2, CH_4, N_2O, CO, SF_6, HCC, HFC, CFCs, Halons, R-40, HCFCs, 1 2-dichloro, N_2F	−5.02E+04 kg $CO_{2\text{-eq}}$ (GWP_{100})	Yes	Yes	Yes
			1 t C_{stored};		n/a		−6.85E+04 kg $CO_{2\text{-eq}}$ (GWP_{100})			

ND = not determined.
[1]Other greenhouse gases were not specified in the study.
[2]Although the study refers to land and water impact, no impact method was applied. Hence, only land and water accounting were addressed.
[3]Power and heat.
[4]Values are given per MJ of fuel as follows: −4.8 to −3.4 g CO2-eq/MJ Ethanol.

NET [63,65,68].

Although achieving negative emissions and mitigating climate change impact, it should be kept in mind the CH_4 fluxes from trees and soils in the forest that were not included in this study due to the lack of local studies and data. Forest ecosystems play a significant role in regulating the climate, and they could either be a source or sink of methane that, in turn, plays its role in the climate dynamics [54]. In this context, soils are a CH_4 sink and may become larger sinks or even turn into sources of CH_4 when their conditions change [54,70]. On the other hand, there is growing evidence that CH_4 is emitted through trees in forest ecosystems, although the processes that regulate gas dynamics in trees are poorly understood [71,72]. According to Feng et al. (2020), there is still considerable uncertainty in estimating CH_4 fluxes in forest ecosystems, although significant progress has been made [54]. It is worth highlighting that the present BECCS case includes the removal of residues from the forest, which is likely to reduce CH_4 emissions [73]. Consequently, further works are necessary to determine the CH_4 fluxes in forest plantations hence improving the estimates of the climate change impact within the set boundaries.

On the side of resources, 12 out of 19 BECCS-LCA studies addressed the impact on either one or two resources (e.g., [2,5,57]). This highlights that the impact on the three resources in question (land, water, and energy) has not been fully addressed (Table 7). This way, comparisons were possible only when the same impact assessment method and FU (1 MWh_e, 1 t C_{Stored}) were applied. That said, only 5 BECCS-LCA studies have 1 MWh_e or similar (e.g., 1 kWh_e) as FU (Table 7). Nonetheless, no comparison can be drawn due to different methodological choices, the lack of impact assessment for both land and water, water type specification and water and land use ratios per FU. For instance, while Bennett et al. (2019) [17] neither specified the type of water (green, blue), nor the impact on water and land was assessed, Schakel et al. (2014) [2] applied ReCiPe method (water depletion, agricultural land use and natural land transformation impact category) and their results were mainly presented in percentage, lacking impact results per FU.

Lastly, the EROI obtained in this study matches in order of

Table A1
Life cycle gas emissions, in kg/year.

	Stage					
	FM	CPT	EG-CCS			
			O&M	MEA production	Plant construction	Plant decommissioning
CO_2	*2.05E+06*	3.14E+06	1.42E+07	5.10E+05	2.13E+06	1.91E+04
CH_4	*1.82E+03*	1.91E+03	3.19E+03	2.23E+03	6.01E+03	0.00E+00
CO	6.89E+03	6.95E+03	2.64E+03	3.84E+02	3.04E+04	0.00E+00
$CHCl_3$	2.56E−03	7.44E−05	0.00E+00	5.96E−04	5.28E−02	0.00E+00
N_2O	1.53E+03	1.12E+02	2.04E+01	7.30E+00	4.47E+01	0.00E+00
NF_3	9.32E−10	1.69E−10	2.44E−10	1.00E−09	3.69E−07	0.00E+00
SF_6	1.09E−02	8.09E−03	4.45E−03	3.18E−02	5.33E−02	0.00E+00
HFC-152a	2.36E−03	1.11E−03	1.53E−04	2.24E−04	1.15E−01	0.00E+00
HFC-134a	1.81E−02	1.11E+00	1.16E−04	2.61E−04	6.45E−02	0.00E+00
CFC-113	1.30E−04	1.43E−06	9.81E−06	2.11E−06	1.86E−03	0.00E+00
1,2-dichloro-	2.93E−01	6.75E−03	7.40E−04	5.27E−04	3.01E+00	0.00E+00
CFC-114	2.54E−03	1.14E−03	8.46E−04	6.30E−03	6.27E−03	0.00E+00
HCFC-124	4.25E−07	5.29E−08	3.96E−08	2.05E−07	3.51E−04	0.00E+00
Halon 1001	1.50E−06	4.62E−08	4.77E−08	2.57E−07	1.10E−06	0.00E+00
Halon 1211	2.89E−03	5.09E−04	1.56E−02	2.60E−03	8.93E−04	0.00E+00
Halon 1301	2.46E−02	3.60E−02	1.04E−03	1.36E−03	4.28E−03	0.00E+00
HCFC-22	1.06E−02	2.28E−03	5.70E−02	8.68E−03	5.73E−01	0.00E+00
HCC-30	3.47E−04	7.52E−05	2.79E−04	1.52E−03	6.92E−03	0.00E+00
HCFC-21	1.60E−06	2.03E−08	1.14E−07	1.75E−08	3.48E−05	0.00E+00
R-40	5.74E−04	1.33E−04	5.02E−04	2.77E−03	7.47E−03	0.00E+00
CFC-10	6.62E−04	4.02E−04	1.17E−03	8.42E−05	7.79E−03	0.00E+00
CFC-11	1.77E−06	2.24E−08	1.26E−07	1.93E−08	3.83E−05	0.00E+00
CFC-12	4.12E−04	9.02E−06	1.13E−04	1.31E−05	2.61E+00	0.00E+00
HFC-23	5.10E−04	6.45E−06	3.63E−05	5.57E−06	4.07E−02	0.00E+00

magnitude with those found in the literature with an exception [63]. Despite this, it should be noted that it was found to be greater than in several studies (e.g., [21,74,75]). It is worth noting that the lack of multi-FU application, methodological choices, absence of ratios per FU, and an appropriate presentation of results, hampers overall comparison with the literature. Hence, this highlights the need to properly assess NETs.

5. Conclusions

A dynamic LCA combined with land-water-energy nexus was applied to assess a negative emission technology classified as BECCS. For such purpose, the recommendations previously made in the literature were followed. In this manner, two FUs were applied, system boundaries were carefully analyzed, a detailed life cycle inventory was given, both carbon accounting and climate change impact were properly addressed, and the impacts on the main resources involved (land-water-energy) were assessed through a nexus approach. The results showed that harnessing RFB for electricity generation and carbon storage accomplished a great positive climate performance. At year 100, the climate change impact was equal to −5.02E+04 kg CO_{2eq}/MWh_e and −6.85E+04 kg CO_{2eq}/t C_{stored}.

Yet, climate change mitigation strategies such as the one here analyzed come at the expense of impacting on land (LUi) and water (Wi). Wi resulted in 11.14 and 356.10 m^3/t C_{stored} for TGWI and RBWP, respectively, while LUi was 3.57E+05Pt/t C_{stored} and 2.61E+05Pt/MWh_e. The amount of land required to generate 1 MWh_e and to store 1 t of C was 0.39 ha and 0.53 ha, respectively. Moreover, an EROI of 3.34 was obtained, being the ratio of biomass-electricity equal to 2.06 t_{RFB}/MWh_e. Land use and water ratios were found to be lower than in other studies. Conversely, EROI was higher than those reported in the literature. Special attention should be paid to the gasifier thermal efficiency since it directly impacts on land, water and energy (EROI).

The results of this study will allow the harmonization of further LCA results and enable comparisons with other LCA-NET studies. Finally, this study contributes to the NET literature as well as information for climate-energy policymaking. Future works should seek to explore different NETs and their technical, economic, and environmental feasibility at the national level. These works should include climate change impact scenarios, water availability, ecosystem services and biodiversity conservation. On the other hand, integrated assessment models, cost-benefit and trade-off analyses could be performed in order to contribute to new knowledge and information, aiming to achieve sustainable development goals.

Table A2
Life cycle C emissions accounting for 25 years.

Stage		kg C-CO_2	kg C-CH_4	kg C-CO
FM		1,40E+07	3,41E+04	7,39E+04
CPT		2,15E+07	3,58E+04	7,45E+04
EG-CCS	O&M	9,66E+07	5,97E+04	2.79E+04
	MEA production	3,48E+06	4,15E+04	5.42E+03
	Plant construction	5,81E+05	4,50E+03	2.42E+04
	Plant decommissioning	5,22E+03	0,00E+00	0.00E+00
Subtotal		1.36E+08	1.76E+05	1.94E+07
Total		**1.37E+08**		

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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Appendix A

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2022.116014.

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