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Research paper

Climate change impacts of power generation from residual biomass

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ABSTRACT

The European Union relies largely on bioenergy to achieve its climate and energy targets for 2020 and beyond.

We assess, using Attributional Life Cycle Assessment (A-LCA), the climate change mitigation potential of three bioenergy power plants fuelled by residual biomass compared to a fossil system based on the European power generation mix. We study forest residues, cereal straws and cattle slurry.

Our A-LCA methodology includes: i) supply chains and biogenic-CO_2 flows; ii) explicit treatment of time of emissions; iii) instantaneous and time-integrated climate metrics.

Power generation from cereal straws and cattle slurry can provide significant global warming mitigation by 2100 compared to current European electricity mix in all of the conditions considered.

The mitigation potential of forest residues depends on the decay rate considered. Power generation from forest logging residues is an effective mitigation solution compared to the current EU mix only in conditions of decay rates above 5.2% a^{-1}. Even with faster-decomposing feedstocks, bioenergy temporarily causes a STR(i) and STR(c) higher than the fossil system.

The mitigation potential of bioenergy technologies is overestimated when biogenic-CO_2 flows are excluded. Results based solely on supply-chain emissions can only be interpreted as an estimation of the long-term (>100 years) mitigation potential of bioenergy systems interrupted at the end of the lifetime of the plant and whose carbon stock is allowed to accumulate back.

Strategies for bioenergy deployment should take into account possible increases in global warming rate and possible temporary increases in temperature anomaly as well as of cumulative radiative forcing.

1. Introduction

Since 2009 the European Union (EU) has been promoting bioenergy as one of the main renewable, low-carbon sources to achieve its ambitious climate and energy targets for 2020 and beyond [1]. More recently, a new EU energy strategy [2] has called for a profound transformation of Europe's energy system, based on a more secure, sustainable and low-carbon economy, with a commitment to achieve by 2030 at least 27% share of renewables on the EU's energy consumption and 40% greenhouse gas emission reduction relative to emissions in 1990 [3].

Bioenergy is currently the major source of renewable energy in the EU. The demand for biomass in the EU and world-wide is increasing, both in the heating and in the power sector. In 2013, renewable sources generated 26% of EU's electricity, and the target is to reach at least 34% of power generation in 2020 and 45% in 2030. Biomass use for electricity grew by 11% per year during period 2005–2012, and it increased further to reach 18.7% of final

Abbreviations: AGTP, Absolute Global surface Temperature change Potential; EC, European Commission; EU, European Union; GHG, Greenhouse Gases; GWP, Global Warming Potential; id, idem; (I)LUC, (Indirect) Land Use Change; LCA, Life Cycle Assessment; NMVOC, Non-Methane Volatile Organic Compound; NTCF, Near-Term Climate Forcers; STR(i)/(c), Surface Temperature Response (instantaneous)/(cumulative); SM, Supplementary Material; SOC, Soil Organic Carbon; WMGHG, Well-Mixed Greenhouse Gases; JRC, Joint Research Centre.

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renewable electricity consumption in 2013. Power produced from biomass is expected to exceed 839 PJ by 2020 [4].

Biomass wastes and residues from forestry and agriculture are expected to fuel part of this growth. Utilities throughout the EU are converting existing coal power plants to wood pellets in order to comply with stricter regulations on carbon emissions (e.g. Refs. [5,6]); logging residues are expected to fulfil part of the pellet demand due to legislation discouraging or forbidding the use of high-quality roundwood for energy [7]. Large unexploited potential of cereal straws is available throughout the EU [8] and some Member States already incorporate straw in their energy mix. The installed capacity of biogas plants have increased steeply within the EU in the last years [9,10]; although most of the current plants operate with a mix of substrates dominated by energy crops, recent legislative changes are expected to strongly promote the use of animal slurry and other agricultural residues [11].

The increasing demand for bioenergy must be reconciled with environmental, economic and social sustainability in Europe and globally. Assessing the potential of bioenergy technologies to mitigate climate change is a complex task. Bioenergy systems can influence directly and indirectly local and global climate through a complex interaction of perturbations [12], including: CO_2 and other long and short-lived climate forcers from biomass combustion, alteration of biophysical properties of the land surface, influence on land use and management, and substitution of fossil fuels and other commodities such as food and wood products.

Life Cycle Assessment (LCA) has emerged as the main tool used to inform policy-makers about potential environmental impacts of bioenergy pathways [13]. Plevin et al. [14] have argued that Consequential LCA (C-LCA) is the appropriate modelling framework to support policy design and to compare the potential impacts of different policy measures. Attributional LCA (A-LCA) studies of bioenergy systems in the past have been unable to properly capture the above-mentioned complexities of bioenergy climate impacts and, consequently, have often been misinterpreted, providing decision-makers with incomplete information [15–19].

Recent debate has brought forward methodological improvements to A-LCA analysis to help tackle some of these limitations. Soimakallio et al. [20] make a compelling case that the use of a baseline or counterfactual, i.e. “the hypothetical situation without the studied product system”, is appropriate in A-LCA and necessary to properly evaluate the impacts of land-based products, such as bioenergy. This is crucial, since the climate change mitigation potential of bioenergy has often been calculated in terms of GHG savings against fossil alternative systems but ignoring the actual land use development without bioenergy production, as highlighted by recent studies [16,21–24].

Further, A-LCA is often applied as a static approach. Emissions and sequestrations at different times are either flattened, as if happening at once at time zero, or annualized over a subjective period of time and discounted fully after such period [25,26]. This can create, at best, ambiguity in the interpretation of the results and, at worst, misrepresent the impact of a technology on the climate [27].

The choice of Global Warming Potential (GWP) as the operative metric under the UNFCCC and Kyoto protocol has made it the metric of reference for the climate change impact category in LCA studies. Nonetheless, the GWP metric is not free from criticism due to its unclear physical meaning and for the possible misinterpretations of short-lived forcers [25,28,29]. Kirschbaum [30] has summarized that impacts of climate change can be linked either to its magnitude (i.e. temperature anomaly above pre-industrial era), to its rate or to its cumulative effect. The use of time-explicit metrics based on the Absolute Global surface Temperature change Potential (AGTP), both in its end-point as well as time-integrated formulation [31,32], can provide valuable insights to impact assessment [25,31].

The aim of this work is to apply all these methodological innovations to an attributional life cycle assessment of the climate impacts of electricity production from three bioenergy systems: 1) Power plant fuelled with pellets from forest logging residues with an electrical capacity of 80 MW; 2) Power plant fuelled with cereal straw bales with an electrical capacity of 15 MW; 3) Anaerobic digestion plant fuelled by cattle slurry with an electrical capacity of 300 kW.

We reckon that our analysis provides valuable information to policymakers on the feedstocks, systems, configurations and management practices that carry potential environmental risks and that should thus not be promoted or, at least, monitored with care.

2. Materials and methods

2.1. Goal and scope definition

The LCA follows an attributional modelling principle. We designed three systems representing three different production scales (see Fig. 1): a) large-scale power plant with a gross electrical capacity of 80 MW fuelled with wood pellets from forest logging residues (FRel); b) medium-scale power plant of 15 MW fuelled with cereal straw bales (STel); c) small-scale internal combustion engine of 300 kW fuelled with biogas produced from anaerobic digestion of cattle slurry, employing an open or gas-tight tank for digestate storage (Biogas OD/CD).

The goal of the analysis is to assess the potential of these bioenergy power plants to mitigate the planet's temperature anomaly compared to alternative systems relying also on fossil sources. The reference alternative system, hereafter called simply reference system, is designed to represent the current EU-27 power generation mix. We refrain from the use of the term “counterfactual” as this may seem to imply a deterministic alternative to the bioenergy use, while we want to emphasize that the conclusions of our study are specific to the systems assumed, including the reference(s). We do not assume perfect substitution; the reference system is used solely to put the climate impacts into context. For this reason we evaluate the sensitivity of the results to multiple assumptions characterizing the bioenergy and the reference system (see Section 2.4).

To facilitate the interpretation of results and connection with existing LCA literature, we divide both the bioenergy and the reference systems into two separate subsystems: supply-chain and biogenic emissions. “Supply-chain” inventories account for all inputs and emissions associated to the energy sector; i.e. collection, transport, processing and end-use. Within this inventory we apply the common approach of zero-rating for biogenic-CO_2 emissions at the point of combustion. In the “biogenic” inventory we account for all biogenic-CO_2 flows. This includes CO_2 emissions from the combustion of biomass (bioenergy) and CO_2 emissions from aerobic decomposition of the uncollected biomass (reference) (Figs. S1 and S2).

The analysis is also divided into two stages. In a first stage we focus solely on the GHG emissions from the supply chains of the three bioenergy systems (Fig. S3). This approach reflects the common assumptions used in A-LCA of bioenergy systems: the analysis is static in time, the climate metric used is GWP at a fixed time horizon of 100 years, the alternative land-use is ignored and so are the dynamics of emission profiles as well as of the climate response. This method also mirrors the sustainability criterion of GHG emissions saving threshold implemented in European legislation [1]. The detailed results from this analysis are presented in the Supporting Material (SM).

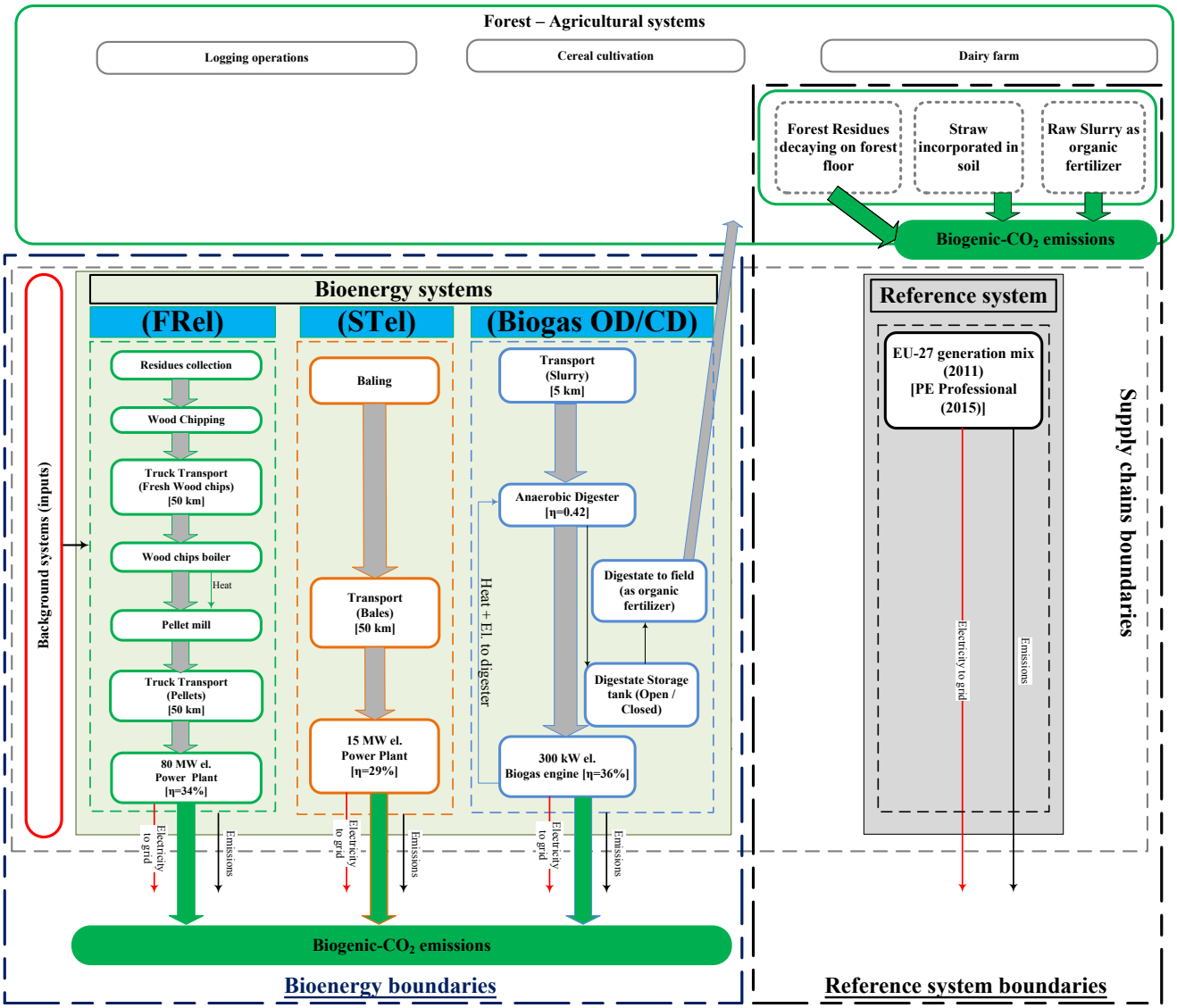

Fig. 1. System boundaries for all the systems considered; on the left are the bioenergy systems and on the right the reference alternative system. Both bioenergy and reference systems include the energy production supply chain ("Supply-chains boundaries") as well as biogenic-CO_2 flows. Details on the systems are given in the text and in the SM. FRel = Forest logging residues pellets used in a power plant with 80 MW gross electrical capacity; STel = cereal straw bales used in a 15 MW gross electrical capacity power plant; Biogas OD/CD = Biogas from cattle slurry used in a 300 kW gross electrical capacity internal combustion engine; with open storage tank for digestate (OD) and with gas-tight tank (CD).

In the second stage we add all biogenic-CO_2 flows, we apply a dynamic analysis and we include the climate response. We present the results in terms of mitigation potential, defined as the net result of Surface Temperature Response (STR) for the bioenergy system subtracted of the STR caused by the reference system. Negative values reflect a potential mitigation compared to the defined alternative.

The functional unit considered is 1 MJ of electrical energy per year at power plant outlet, including own consumption but no transmission and distribution losses. The geographical scope of the paper includes the EU-27 countries. Infrastructures are not included. The software used was Gabi 6.3 [33].

2.2. Life cycle inventory (LCI)

2.2.1. Supply chain inventory

All the datasets related to collection and processing of the residues were the same as the ones presented in Ref. [34]. We modified a few assumptions compared to the JRC report, concerning end-use emissions, transport distances, climate metrics and background systems datasets. The life cycle inventory is detailed in the Supporting Material. Details of each system are reported in Table 1.

Within the reference system, we consider that the energy function is provided by the current EU-27 average power generation mix. This process is taken from the Gabi Professional database [33] and it considers emissions from the whole electricity mix, renewables included, calculated for the year 2011. Data for two additional fossil systems, coal and natural gas power plants, are presented in the SM.

2.2.2. Biogenic inventory

We assume a "business-as-usual" baseline because the feedstocks we consider are residues only in the context of current

Table 1
Summary of all the parameters used in the base cases of the bioenergy and reference systems.

System ID	System description	Supply-chain inventory	Biogenic-CO2
FRel	Bioenergy system: Wood pellets from forest logging residues combusted in a large-scale power plant (80 MW).	Main processes (details in SM): 1. Collection and chipping of residues (Table S6) 2. Transport by truck to pellet mill for 50 km (Table S9) 3. Pelletization (Table S10) 4. Combustion in 80 MW power plant (Table S14) Background processes represent EU averages and are taken from Gabi Professional database and are static in time.	Total wood necessary to produce 1 MJ of electricity, including losses and additional quantity to use in boiler at the pellet mill: 0.205 kg MJ-1 (on a dry matter basis). All carbon is assumed to be released as CO2 by combustion at the year of collection: 0.376 kg MJ-1. See Table S1 for physico-chemical properties of forest residues
Ref_FRel	Reference system for FRel	EU-27 Mix dataset, including fossil and renewable sources. Dataset from Gabi Professional database. Constant over the whole timeframe considered.	Total wood necessary to produce 1 MJ of electricity is considered to be added on the forest floor each year: 0.205 kg MJ-1 (on a dry matter basis). All carbon is assumed to be released as CO2 by aerobic decomposition on the forest floor. Decay trend is detailed in Eq. S1 and Fig. S1. The mass decay rate for the residues is considered to be equal to 11.5% a-1
STel	Bioenergy system: Cereal straw bales combusted in a medium-scale power plant (15 MW)	Main processes (details in SM): 1. Collection and baling of straw (Table S7) 2. Transport by truck to power plant for 50 km (Table S9) 3. Combustion in 15 MW power plant (Table S14) Background processes represent EU averages and are taken from Gabi Professional database and are static in time.	Total straw necessary to produce 1 MJ of electricity, including losses: 0.2 kg MJ-1 (on a dry matter basis). All carbon is assumed to be released as CO2 by combustion at the year of collection: 0.294 kg MJ-1. See Table S2 for physico-chemical properties of straw
Ref_STel	Reference system for STel	EU-27 Mix dataset, including fossil and renewable sources. Dataset from Gabi Professional database. Constant over the whole timeframe considered.	Total straw necessary to produce 1 MJ of electricity is incorporated in the soil each year: 0.2 kg MJ-1 (on a dry matter basis). All carbon is assumed to be released as CO2 by aerobic decomposition in the soil. The decomposition trend is obtained from the results presented in [36] and the decay model used is detailed in Eq. S2, Eq. S3 and Fig. S2. The mass decomposition rate for straw is considered to be the one obtained for average EU28 conditions.
Biogas OD/CD	Bioenergy system: Dairy cattle slurry anaerobically digested to produce biogas to be combusted in an internal combustion engine (300 kW). Digestate is stored in an open or closed tank.	Main processes (details in SM): 1. Transport by truck of raw cattle slurry to anaerobic digestion plant for 5 km (Table S9) 2. Anaerobic digestion plant (Table S11). 1% of the CH4 produced is considered to leak from the plant. 3. Digestate storage in open or gas-tight tank (Table S12). Emissions from the closed tank are considered to be 2% of the emissions from the open tank due to membrane permeability. 4. Digestate application on field as organic fertilizer (Table S13) 5. Combustion of biogas in 300 kW internal combustion engine (Table S14) Background processes represent EU averages and are taken from Gabi Professional database and are static in time.	Total slurry necessary to produce 1 MJ of electricity from OD/CD system, including losses: 0.60 / 0.54 kg MJ-1 (on a dry matter basis). Biogenic CH4 emissions are included in the supply-chain inventory. All the remaining carbon is considered to be released as biogenic-CO2. Digestate is considered to decompose at the same rate as the slowest component of the raw slurry and thus this component cancels out with the reference system and it was not calculated explicitly. See Table S3 for physico-chemical properties of slurry and biogas
Ref_OD/CD	Reference system for Biogas OD/CD	EU-27 Mix dataset, including fossil and renewable sources. Dataset from Gabi Professional database. Constant over the whole timeframe considered. Main processes for raw cattle slurry management (details in SM): 1. Raw slurry storage in open tank (Table S15) 2. Raw slurry application on field as organic fertilizer (Table S16)	Total slurry necessary to produce 1 MJ of electricity from OD/CD system, is stored and applied on field each year: 0.60 / 0.54 kg MJ-1 (on a dry matter basis). Biogenic CH4 emissions are included in the supply-chain inventory. Biogenic-CO2 is considered to be released in the same quantity as for the biogas system in the year of collection. The amount of stable carbon in the raw slurry applied on the field is considered to be the same amount, and to decay with the same rate, as the carbon in the digestate.

existing industrial operations, i.e. timber logging, cereals cultivation and dairy industry. The consequence of this choice is that emissions from upstream operations are identical in both the bioenergy and the reference systems and thus they cancel out and are not reported here. Marginal differences caused by the additional removal of residues for bioenergy are considered in the sensitivity analysis for straw management.

We designed our reference system considering that the collection and energy use of the residual feedstocks analysed here is often not economically profitable without incentives and thus these feedstocks would not be collected or utilized without demand for bioenergy. Forest logging residues in Europe are commonly left on the forest floor; more rarely they may be burned at roadside. Our reference system assumes that the deadwood left in the forest would decompose following an exponential decay (Eq. S(1)); the kinetics of decomposition varies depending on the wood type, wood size and climate conditions [35]. A standard decay rate for branches with diameter between 10 and 30 mm, was defined for average conditions in boreal and temperate regions, equal to 11.5% a^{-1}.

Cereal straws can have several commercial uses, from animal bedding to building material, as well as being incorporated in agricultural land as soil amendment or used for soil surface mulching. Our reference considers that straw is incorporated in the agricultural soil every year. In this case, a continuous removal of straw causes a gradual decrease in the content of soil organic carbon (SOC). Lugato et al. [36,37] used the CENTURY agroecosystem model to assess the impact of several management alternatives of agriresidues on SOC stocks and sequestration rates in each EU-28 member state projected until 2100. We applied their results to obtain the decomposition parameters for straw incorporation and subsequent biogenic-CO_2 emissions in the reference system (see SM for details).

Cattle slurry, if not anaerobically digested, is commonly stored on-farm in open tanks and then used as organic fertilizer and soil amendment. This type of slurry management causes high emissions of methane and nitrous oxides (see Tables S15 and S16). On the contrary, when slurry is processed via anaerobic digestion and the biogas is collected and combusted for bioenergy, methane emissions are significantly lower [38]. The digestate residue from anaerobic digestion can then be used as organic fertilizer and it is reasonable to assume that the fertilizing potential of raw slurry is equal to the one of digestate [10,39,40]. Finally, when digestate is applied on agricultural fields rather than raw slurry, its lower content of C could potentially cause a lower accumulation of soil organic matter in the long-term. Results are not yet clear on the magnitude of this phenomenon, but existing empirical research as well as model results, suggest the impact to be short-term and almost negligible [40,41]. For the reasons above, the anaerobic digestion process covers all the same functions as the reference system (energy, organic fertilizer and soil amendment) and we have not included any marginal impact.

2.3. Climate metrics and dynamic LCA

In the case of transient emission profiles, such as the ones associated to the decomposition of biomass on the forest floor, or in agricultural soils, the use of simplified, normalized climate metrics is problematic. Especially annualization of emissions can create situations in which certain pathways may appear to pass or fail GHG emission savings thresholds depending on the annualization period chosen [42–45].

We reckon that an explicit treatment of time makes interpretation of the results much clearer. Thus we have defined dynamic emission profiles for all processes: we consider the supply-chain inventory to be constant each year in which the functional unit is delivered; the biogenic-CO_2 inventory has its own dynamic trend linked to the aerobic decomposition of the residues (see SM and Figs. S1 and S2).

We then convolute the emission profiles with the instantaneous and time-integrated formulation of the Absolute Global surface Temperature change Potential (AGTP) metric to calculate the Surface Temperature Response (STR) to the systems by 2100. We present the Surface Temperature Responses calculated as an instantaneous (STR(i)) and as a cumulative (STR(c)) metric. The latter can be numerically assimilated to the Absolute Global Warming Potential metric [46] but with a clearer physical basis.

A description of the model, equations and parameters used, based on the work of Myhre et al. [47], Aamas et al. [32] and Cherubini et al. [31], can be found in Ref. [42].

Because of the uncertainties associated to the climate metric and to the input values, our goal is not to quantify the magnitude of absolute temperature responses but rather to assess the climate mitigation of the various bioenergy systems relative to various alternative systems.

We consider two cases representative of possible energy system developments in the future: Case 1) a continuous production of 1 MJ of electricity to the grid each year. This case represents a hypothetical systemic change in which bioenergy becomes permanently part of the power generation mix; Case 2) a sustained production of 1 MJ of electricity to the grid for 20 years, considered to be the lifetime of the power plants, after which biomass reverts to its reference use, natural decomposition. This case considers bioenergy as a transitional solution towards a power mix based on other, carbon free, renewable resources.

2.4. Base cases and sensitivity analysis

We are conscious that the systems defined and analysed in the base cases are only one snapshot of the many configurations and parameters that may characterize real power generation systems. In order to facilitate the interpretation of our results, we first defined the systems in their base case (Table 1) and the results in Section 3.1 refer to these conditions.

However, we then varied multiple parameters to account for the influence of: i) site-specific and geographic conditions; ii) feedstock types and characteristics; iii) different agronomical solutions; iv) accidental leakages; v) decarbonized European power generation mix.

Table 2 illustrates all the combinations and parameters variations compared to the base cases. We identified variables that influence the final result because of multiple permutations possible in the reference system (*Indirect sensitivity*). These parameters are not directly an attribute of the bioenergy system but can define situations where promotion of bioenergy may be more or less beneficial in terms of climate change mitigation. We then identified factors which are direct attributes of the bioenergy system and can thus be influenced when setting up legislation (*Direct sensitivity*).

Giuntoli et al. [42] showed that the decay rate of logging residues left on the forest floor is one of the main factors influencing the STR of domestic heat produced from this feedstock. We tested the variability of results with this parameter also in this study.

Concerning STel, we firstly analysed the influence of the geographic origin of the feedstock by considering the SOC trends for various European countries from Lugato et al. [36] and from Powlson et al. [48]. Secondly, we designed three scenarios to test the sensitivity to three factors which have large uncertainties: soil emissions, farming practices and soil productivity. In Scenario 1 we assumed that the removal of straw caused lower emissions of N_2O from the soil because of less N incorporated with residues

Table 2
Summary of the parameters varied in the sensitivity analysis.

System ID	Parameter considered	Base case	Indirect parameters (linked with attributes of the reference or fossil alternative system)	Direct parameters (linked with attributes of the bioenergy systems)	Storyline
Ref_FRel	Decay rate on forest floor	11.5% a^{-1}	2% a^{-1} ÷ 40% a^{-1}		Verify the influence of different logging residues types or geographical origin affecting the decay rate on the forest floor.
FRel	EU-27 grid mix	EU-27 Mix dataset, including fossil and renewable sources. Dataset from Gabi Professional database. Constant over the whole timeframe considered.		EU-27 Mix emissions dynamic in time according to PRIMES 2013 reference scenario [68]	Verify the influence of a decarbonized EU-27 power generation mix. Emissions from electricity consumption in the FRel pathway during pellet production are recalculated with the updated dataset.
Ref_STel	Decomposition trend of straw in the soil	Average result over the whole EU-28	Decomposition trend for all European Member States. Only extreme cases are reported: Estonia and Portugal		Verify the influence of the geographic origin of the straw affecting the decomposition trend in the soil.
STel.	Nutrient management and soil emissions	a. Macro-nutrients removed with straw are not compensated; b. Cereal grain long-term yields are not affected by straw removal; c. N_2O emissions from soil are not affected by the removal of straw		1. Scenario 1: a. Macro-nutrients are not compensated; b. Cereal grain long-term yields are not affected; c. Reduced N_2O emissions for removal of straw-N considered. 2. Scenario 2: a. Macro-nutrients are compensated by synthetic fertilizers; b. Cereal grain long-term yields are not affected; c. Net N_2O emissions considered (additional emissions for synthetic N-fertilizer − reduced emissions for removal of straw-N). 3. Scenario 3: a. Macro-nutrients are compensated by synthetic fertilizers; b. Cereal grain long-term yields are assumed to decrease by 8% in the long-term and an ILUC emission factor is applied;[a] c. Emissions of WMGHG for cultivation of additional cereal grains are included.	Verify the influence of potential agronomic management solutions, soil emissions and soil productivity changes.
Biogas OD/CD	Accidental methane emissions + Emissions through membrane permeability (Biogas CD)	1% of the methane produced is lost as accidental leakages from the plant. Emissions from digestate storage in Biogas CD are equal to 2% of emissions from open tank.		Methane accidental leakages: 0% ÷ 5% of the methane produced Digestate storage emissions in Biogas CD: 0% ÷ 2% of digestate emissions in case of open tank.	Verify the influence of accidental or structural leakages of methane from biogas plants.
Ref_FRel and Ref_STel	Technology mix	EU-27 Mix dataset, including fossil and renewable sources. Dataset from Gabi Professional database. Constant over the whole timeframe considered.	1. Technology mix is updated with a time step of 10 years between 2010 and 2050 and left constant afterwards. According to data from PRIMES in the latest EU-28 reference scenario [68]. See SM for details. 2. Power generation from hard coal. Dataset is taken from Gabi professional database for EU-27 average. 3. Power generation from natural gas. Dataset is taken from Gabi professional database for EU-27 average.		Compare bioenergy systems to a dynamically decarbonized power generation mix. Compare bioenergy systems to two marginal technologies (based on coal and natural gas) that may be displaced by bioenergy.

[43,49,50]. In Scenario 2 we assumed that farmers will compensate the macro-nutrients removed with the straw by applying the same amount of additional mineral fertilizers (N, P, K) [45,50]. In Scenario 3 we considered a worst-case in which despite compensating for lost nutrients, the decrease in SOC and subsequent degradation of soil physico-chemical properties leads to a long-term decrease in cereal grain yield. This, in turn, affects global cereal markets causing similar effects to the ones analysed in Indirect Land Use Change (ILUC) literature [51,52].

The climate impact of biogas systems is mainly linked to the overall methane emissions from the plant. Because of the large differences in GHG emissions between AD plants with an open digestate storage tank and a gas-tight tank [53], we treated these two technological options as two separate systems and defined two separate base cases (Biogas OD/CD). Additional to digestate storage emissions, fugitive methane emissions have mostly been measured at pipeline connections and during non-regular functioning of the plant. Some plants are equipped with a flare, but this mostly happens in newer and larger facilities; in many small plants like the one modelled here, the methane may be simply vented. To verify the influence of these potential emissions, we varied the value of accidental methane leaks from zero to 5% of the methane produced. This reflects the high range of emissions recorded for normal operations of biogas plants [54].

3. Results

3.1. Climate impact: surface temperature response and mitigation potentials

Fig. 2 illustrates the mitigation potential for the four bioenergy systems analysed versus the reference system, in their base case. It is clear that at the year 2100, all bioenergy systems guarantee a mitigation of the STR(i) compared to the current power generation mix.

However, the mitigation of the FRel system is delayed by 47 years, in case 1, and by 30 years in case 2. This is caused by the temporal imbalance between the carbon emissions due to natural decay of logging residues and the carbon emissions due to instantaneous oxidation during wood combustion to produce electricity. After ca. 40 years the rate of biogenic-CO_2 emissions in the bioenergy system becomes equal to the rate in the reference system and the supply-chain emissions become more and more relevant. Fig. 3a–b shows that the STR(i) of net biogenic-CO_2 emissions, defined as CO_2 from combustion subtracted of CO_2 from natural decay, dominate for the first 130 years over the STR(i) impact of bioenergy supply chains. Only after that time, supply-chain emissions become the main climate forcer. Results are different for case 2: after 50 years, only the fossil CO_2 from the supply-chain operations remains in the atmosphere and the mitigation potential of the bioenergy system can be calculated excluding biogenic-CO_2 emissions. When considering time-integrated results (Fig. 2c–d), the FRel system barely guarantees any mitigation potential by 2100.

The STel system also shows a temporal delay of 13 years before achieving mitigation. However, the magnitude of the climate change worsening is only 16% of the one caused by the FRel system. This worsening is propagated in the STR(c) results so that mitigation is achieved only after 20 years. It is interesting to note that the cooling effect of emissions of NTCF, especially NOx and SOx (Fig. S4), dominates over the warming impact of WMGHG (Fig. 3c–d). This is a trade-off with other harmful environmental impacts associated to these pollutants such as secondary particulate matter formation, acidification and photochemical ozone formation [55,56].

The biogas systems have the capacity to provide ten times the climate change mitigation by 2100 compared to the system based on forest residues pellets. This is due to the fact that raw slurry management generates a much higher STR(i) compared to anaerobic digestion.

3.2. Sensitivity analysis

3.2.1. Indirect sensitivity of results to site-specific characteristics

The decay rate of the undisturbed logging residues on the forest floor can vary largely due to many factors: climatic conditions, wood type, wood size etc. By condensing all possible variables into a single parameter, the decay rate, our approach can be applied independently from the specific conditions that generated such decay rate.

Fig. 4 shows the results of the STR(i) for logging residues when the decay rate in the forest is varied between two hypothetical values: 40% a^{-1} (e.g. fast decaying leaves and needles) and 2% a^{-1} (e.g. slow-decaying coarse deadwood). In case of a systemic transition to bioenergy (case 1), utilizing logging residues with a decay rate lower than 5.2% a^{-1} would not cause any climate change mitigation by 2100 as compared to the current power generation mix. Even in case of bioenergy as a transitory option, investing for the next 20 years in slow-decaying feedstocks would barely guarantee any advantage by 2100 compared to continuing with the current power mix.

Fig. 5 shows the range of impacts for STel systems when considering straw decay rates for various European countries. From the results of the model of Lugato et al. [36], it appears that the impacts of removal of straw on the SOC stock do not differ greatly among the various European countries. Estonia shows the highest value and Portugal the lowest, albeit neither of the two countries is a large producer of cereals. It is important to remember that the values presented here are an average of all the spatial units within a country where the amount of cereal straw, varied in the simulations, is also constrained by its local availability. They represent, then, an average condition that may differ at a local level. This is the case of the results obtained by Powlson et al. [48] (also shown in Fig. 5); they modelled a continuous straw incorporation of 4.25 t ha^{-1} dry matter basis in a fine silty-clay-loan soil, resulting in a higher impact of the bioenergy system than the reference for the first 26 years. Indeed, looking at the regional values in South-East England in Lugato et al. [36], SOC changes appear consistent with the case study investigated by Powlson et al. [48].

3.2.2. Direct sensitivity of results to bioenergy system configurations

Fig. 6 illustrates the mitigation potential for three different scenarios of the STel pathway. Even Scenario 3 delivers large warming mitigation by 2100 despite the increasingly conservative assumptions. Furthermore, the contribution of ILUC emissions is almost negligible compared to the emissions incurred for additional synthetic fertilizers production and for the cultivation of additional cereals (Fig. S5).

Fig. 7 shows that slurry-based biogas systems can provide a large climate change mitigation despite the conservative range of accidental emissions of methane tested. In fact, even the worse technological configuration, open digestate store, would still be better than the reference alternative as long as less than 6.4% of the methane produced was vented or lost.

4. Discussions

Our findings are in line with other studies assessing the climate change impact of forest and agricultural residues [21,38,57–59]. We

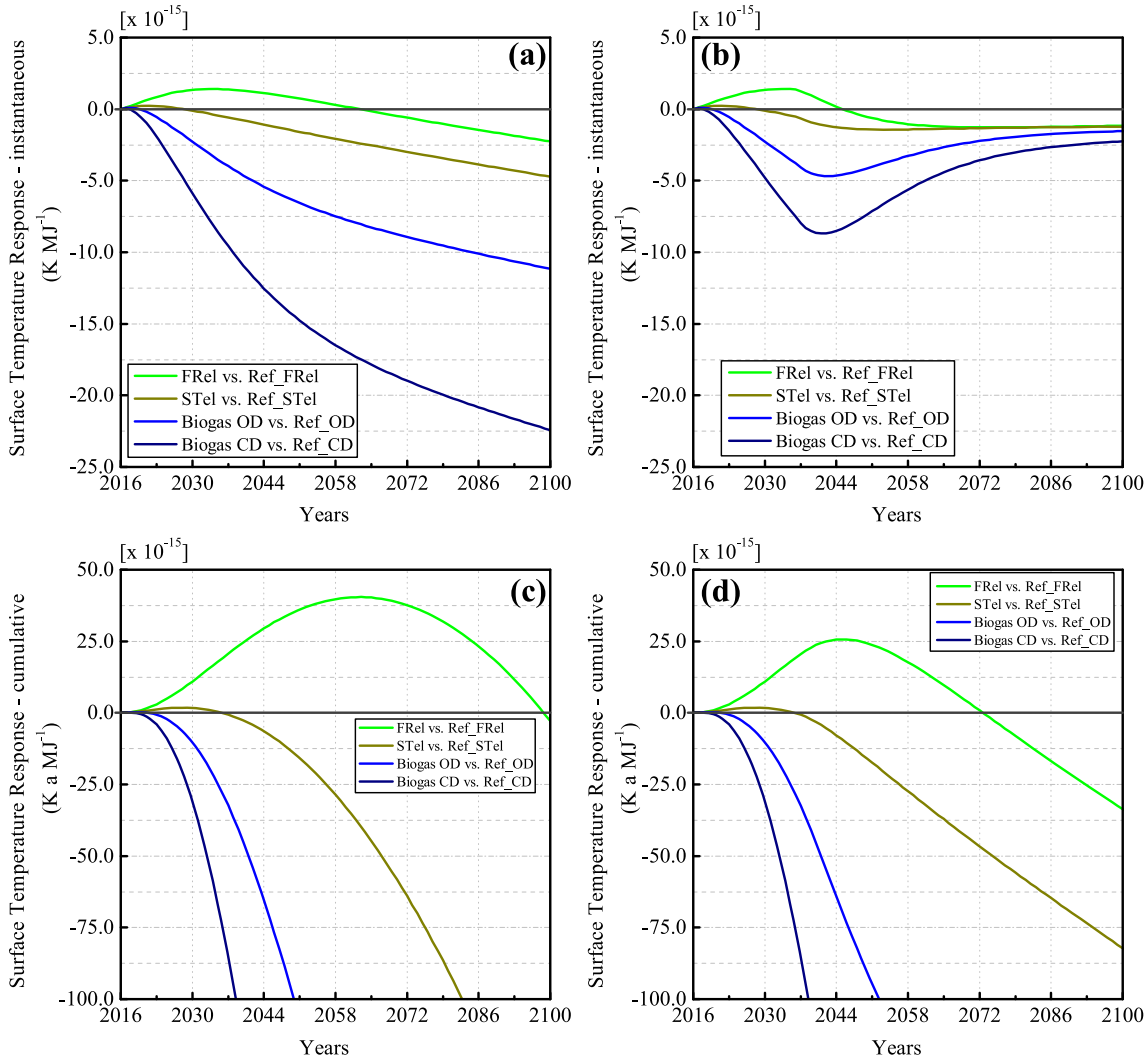

Fig. 2. Mitigation potentials of all the bioenergy systems studied compared to their reference system. Mitigation potential is defined as the net result of Surface Temperature Response (STR) for the bioenergy system subtracted of the STR caused by the reference system; negative values indicate potential climate change mitigation by bioenergy; positive values indicate a climate change worsening. All systems are in their base cases: forest residues with a decay rate of 11.5% a^{-1}; straw decomposition rate average for EU-28 conditions; EU-27 power generation mix supply chain emissions. (a) STR (instantaneous) for systems with emission profiles relative to the production of 1 MJ of electricity per year (Case 1); (b) STR(i) for systems operating for 20 years (Case 2); (c) STR (cumulative) for systems with emission profiles relative to the production of 1 MJ of electricity per year (Case 1); (d) STR(c) for systems operating for 20 years (Case 2). FR el = Forest residues pellets 80 MW plant; STel = Cereal straw bales 15 MW plant; Biogas OD/CD = Cattle slurry anaerobic digestion with open/close digestate tank, 300 kW engine.

confirm that even when biogenic-CO_2 emissions are properly accounted for, all the systems analysed in their base case provide warming mitigation by 2100 compared to the average European power generation mix. The magnitude of such mitigation varies from system to system: slurry-based biogas plants have the highest potential to mitigate global warming and decentralized straw-based plants may also guarantee significant mitigation compared to the current power mix. Large-scale centralized plants based on logging residues provide the least mitigation by 2100.

We have shown that analyses focussing only on supply-chain emissions and only on WMGHG are not complete. For instance, excluding biogenic carbon emissions for logging residues systems would overestimate the mitigation potential of the system by 45% in 2100. On the other hand, excluding NTCF would underestimate the overall mitigation potential of the pathway by 27%. Accounting only for supply-chains emissions is only appropriate when estimating the long-term impact of a system where bioenergy is implemented only temporarily and the carbon stock is allowed to revert to the original level (Case 2 in our analysis); the "long-term" horizon in this case may be as long as two centuries when slow-decaying residues are considered.

We have shown that parameters specific to the site where the feedstock is sourced largely influence the impact on climate of bioenergy systems. The variability of the results to these factors is mainly illustrative because decision makers may have no power to influence them via bioenergy-specific legislation; however, critical or less-than-optimal instances could be excluded from subsidies schemes. For instance, our analysis highlights that caution is required when promoting the use of logging residues with decay rates below 5.2% a^{-1} (i.e. stumps and coarse deadwood in temperate and boreal climates) since global warming mitigation compared to the current EU power generation mix will likely not be achieved before 2100. This value is indicative as it can increase or decrease depending on the alternative system considered.

Nonetheless, all the remaining bioenergy pathways perform better than the reference alternative even when considering

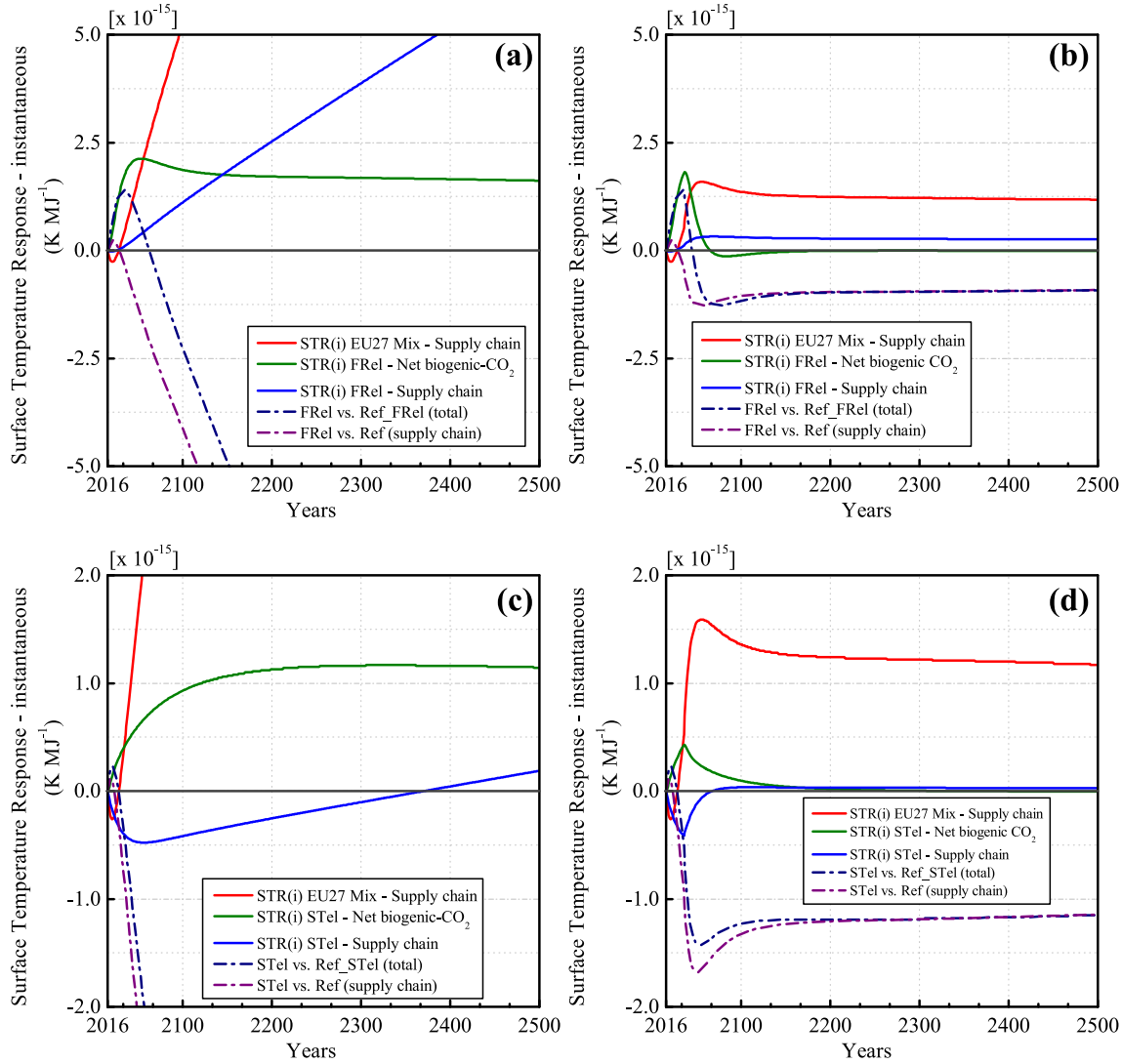

Fig. 3. Contribution of supply-chain emissions and biogenic-CO_2 emissions to the Surface Temperature Response (instantaneous) to a sustained emission profile for FRel and STel systems in their base case. (a) STR(i) for the FRel system with emission profiles relative to the continuous production of 1 MJ of electricity per year (Case 1); (b) STR(i) for the FRel system operating for 20 years (Case 2). (c) STR(i) for the STel system with emission profiles relative to the continuous production of 1 MJ of electricity per year (Case 1); (d) STR(i) for the STel system operating for 20 years (Case 2).

several possible system configurations and when stressing the systems with strongly conservative test cases. The straw pathway, specifically, has the potential to guarantee climate change mitigation by 2100 even when potential soil productivity losses are considered. Even so, SOC content preservation has many benefits beyond climate change mitigation and it is also a priority of the EU Common Agricultural Policy [60]. Systemic approaches should be developed to study the inclusion of biomass production into agricultural rotations in order to retain soil organic carbon and soil health [49]. Other studies have defined site-specific sustainable removal rates for straws so that the SOC level does not decrease in time [61]. While this may be a reasonable definition under agronomic criteria, it is important to point out that the foregone carbon sequestration of the straw removed equates to additional emissions assigned to the bioenergy pathway. Simply put, SOC-related biogenic-CO_2 emissions are proportional to the amount of straw removed [43].

Even though many studies recognize the need to include biogenic carbon emissions, the treatment of time in much LCA literature remains an important source of ambiguity [44,45]. The treatment of dynamic emission profiles is critical: annualizing emissions can present serious difficulties to the interpretation of the results. Fig. S8 illustrates this example using the FRel and STel systems: in the case of logging residues, annualizing net biogenic-CO_2 emissions over 20 or 30 years would indicate higher overall GHG emissions than the reference system. For STel system, the 70% threshold of GHG savings would only be achieved if SOC-related emissions were annualized over 100 years. These results do not provide clear information to decision-makers. The use of the absolute formulation of climate metrics partially solves this ambiguity by illustrating explicit results in time that can be then evaluated according to the specific goal of the analysis.

Further, different types of metrics provide different types of information. Studies in the literature have mainly used cumulative metrics, such as cumulative radiative forcing [58] or normalized GWP factors [21,62]. However, an instantaneous metric such as AGTP can better represent the climate change impacts associated with increasing surface temperatures, such as heat waves and extreme weather events. The STR(i) results are also more suitable to evaluate the contribution of technologies towards internationally

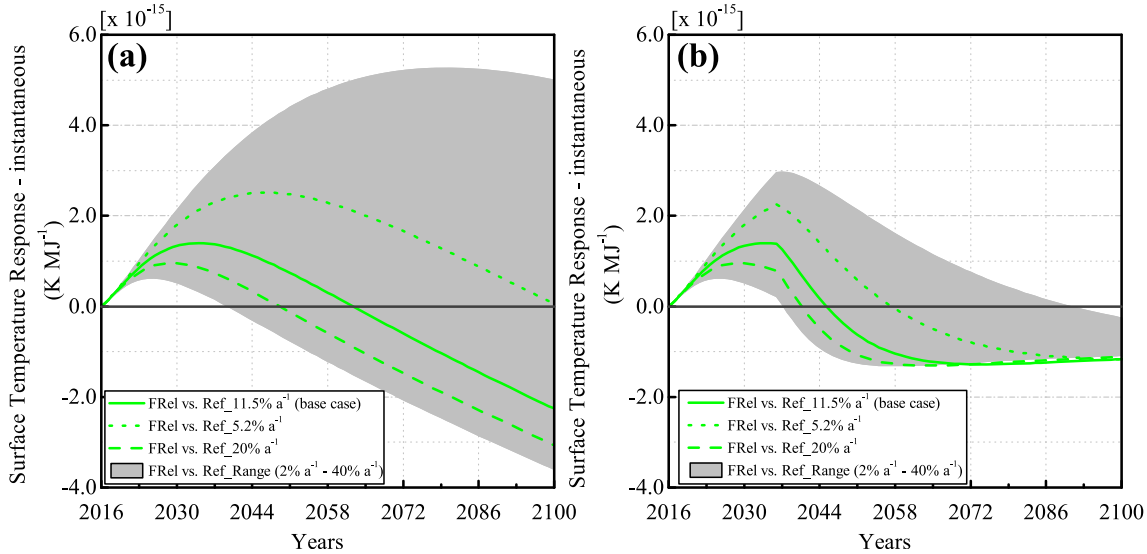

Fig. 4. Sensitivity to forest residues decay rate of the mitigation potential of FRel system compared to the reference. Mitigation potential is defined as the net result of Surface Temperature Response (STR) for the bioenergy system subtracted of the STR caused by the reference system; negative values indicate potential climate change mitigation by bioenergy; positive values indicate a climate change worsening. (a) STR(i) for a system with emission profiles relative to the production of 1 MJ of electricity per year (Case 1); (b) STR(i) for a system operating for 20 years (Case 2). The grey-filled area represents the range of mitigation potentials when different decay rates for the biomass feedstock are considered. The solid-green curve represents the base case of branches (11.5% a^{-1}), the dashed-green curve represents fast decaying residues (e.g. leaves and needles) and the dotted-green curve represents a "critical" decay rate for which the STR(i) at year 2100 is equal between bioenergy and the reference system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

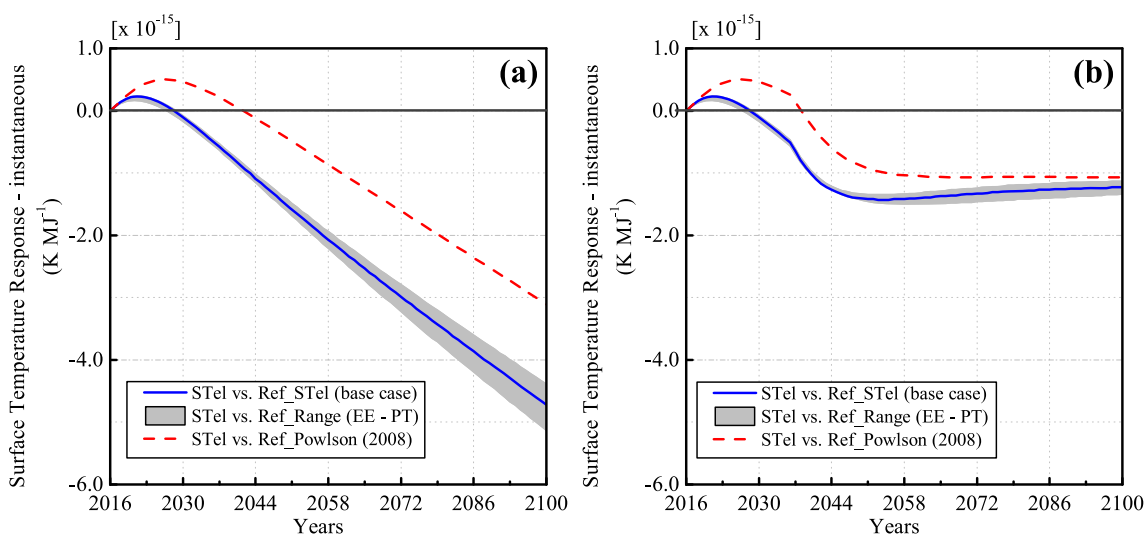

Fig. 5. Sensitivity to the geographic origin of cereal straw of the mitigation potential of STel system compared to the reference alternative. Mitigation potential is defined as the net result of Surface Temperature Response (STR) for the bioenergy system subtracted of the STR caused by the reference system; negative values indicate potential climate change mitigation by bioenergy; positive values indicate a climate change worsening. (a) STR(i) for a system with emission profiles relative to the sustained production of 1 MJ of electricity per year (Case 1); (b) STR(i) for a system operating for 20 years (Case 2). The grey-filled area represents the range of STR when the straw decay for EU Member States is considered; only the maximum and minimum values are shown (Estonia (EE) and Portugal (PT)). The solid-blue curve represents the base case of average EU-28 conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

agreed targets and stabilization scenarios. The explicit formulation in time also provides information on the rate of warming associated to the technologies studied. Cherubini et al. [63] have shown that the impact of biogenic-CO_2 emissions could be assimilated to the one due to short-lived GHGs. This is confirmed by our results. Edwards and Trancik [64] have highlighted that the contribution of technologies characterized by high emissions of NTCF to mitigation scenarios will change depending on the rate and timing of their deployment. Our results show that a high rate of penetration of bioenergy plants may cause a higher rate of warming before actually providing mitigation and that mitigation benefits shift in time with the time of deployment of the technology. Finally, sea level rise has been linked to the total energy accumulated in the planet system [65,66]; thus a cumulative metric is more appropriate to capture the potential risks linked to this phenomenon. Our STR(c) results follow a similar trend to the STR(i) curves but the timing of mitigation and magnitude of the temporary warming worsening for the forest residues pathways should be kept in mind when planning mitigation scenarios.

Awareness of the limitations of this study is essential to properly

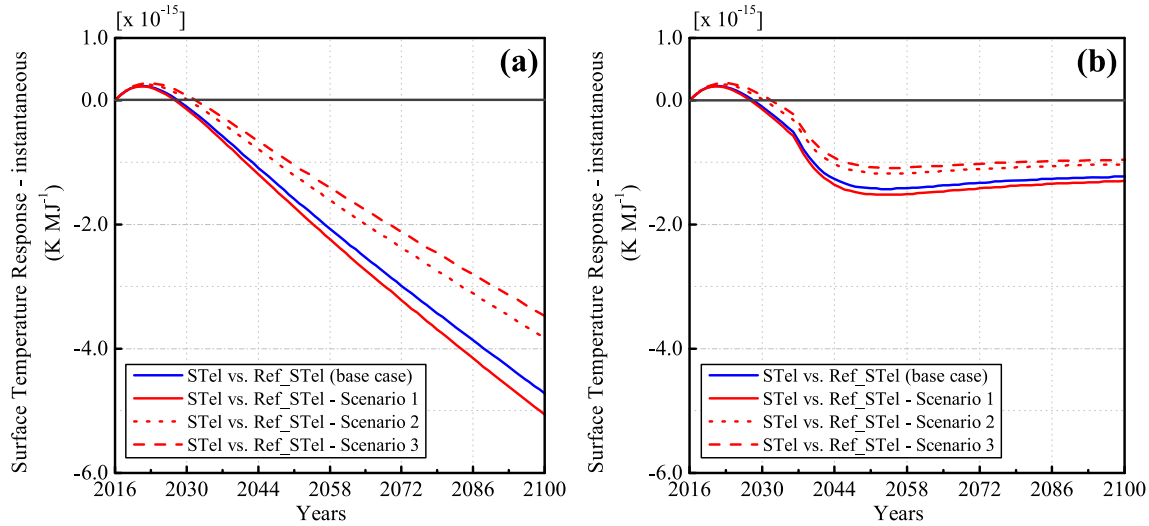

Fig. 6. Sensitivity of the mitigation potential of STel system to alternative nutrient managements to compensate straw removal. The reference system considers straw decay rate for EU28 countries (base case). Mitigation potential is defined as the net result of Surface Temperature Response (STR) for the bioenergy system subtracted of the STR caused by the reference system; negative values indicate potential climate change mitigation by bioenergy; positive values indicate a climate change worsening. (a) STR(i) for a system with emission profiles relative to the production of 1 MJ of electricity per year (Case 1); (b) STR(i) for a system operating for 20 years (Case 2). The three scenarios are described in details in the text: 1) Scenario 1 considers no compensation of lost nutrients and no loss of yield. Avoided N_2O emissions from straw removal are included; 2) Scenario 2 considers that macro-nutrients removed with straw are compensated with synthetic fertilizers and no yield losses of grains. Avoided N_2O emissions from straw removal are included; 3) Scenario3 considers compensation of lost nutrients, loss of yield causes Indirect Land Use Change (see SM for details). Avoided N_2O emissions from straw removal are included.

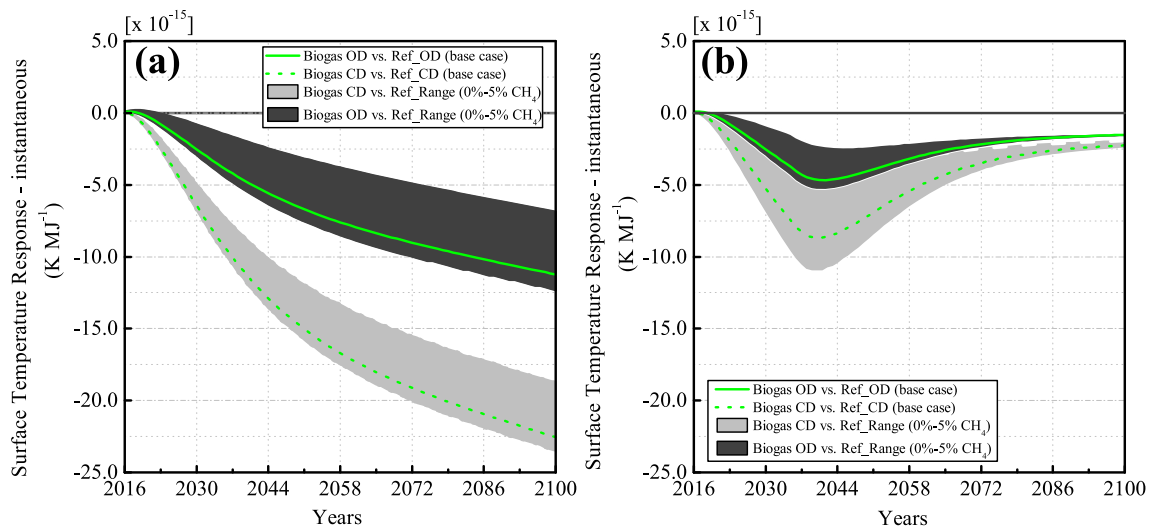

Fig. 7. Sensitivity to increased accidental losses of methane of the mitigation potential of biogas systems. Mitigation potential is defined as the net result of Surface Temperature Response (STR) for the bioenergy system subtracted of the STR caused by the reference system; negative values indicate potential climate change mitigation by bioenergy; positive values indicate a climate change worsening. (a) STR(i) for a system with emission profiles relative to the production of 1 MJ of electricity per year (Case 1); (b) STR(i) for a system operating for 20 years (Case 2). The grey and black areas represented the variation of the results when accidental leakage of CH_4 is varied between 0% and 5% on energy basis, of the produced methane. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

interpret the results. Firstly, market-mediated effects are not considered here and our results apply solely to system configurations equal or similar to the ones studied. For instance, the removal of logging residues may trigger changes in forest management aimed at increasing carbon stocks [67] or cereal straws may be displaced from other markets rather than from their function as soil amendment. Further, in this study we only focus on climate change, however, other potential risks for local air pollution and impacts on biodiversity associated to these technologies should not be underestimated. In previous works [10,11,39,55] we showed that, when promoting the deployment of bioenergy, a holistic approach is essential to identify all potential environmental risks and consequently to design appropriate protective measures. Thirdly, the deployment of bioenergy may have positive strategic consequences on security of energy supply and rural development that are not included in this study.

Finally, we compared the bioenergy pathways to a reference system considering the current average EU-27 power generation mix extrapolated to 2100. However, it is reasonable to expect a continuous decrease in the share of fossil sources and an increasingly decarbonized electricity mix. We tentatively recreated a dynamic EU-27 power mix STR(i) based on the reference scenario 2013 of the European Commission [68] (see SM and Fig. S7) and we show that our conclusions remain valid. Nonetheless, dynamic

background processes should be developed and used more commonly in A-LCA studies.

5. Conclusions

We have analysed the climate change mitigation potential of three power generation systems fuelled by three different types of biomass residues: forest logging residues, cereal straw and dairy cattle slurry.

We applied various methodological innovations that help to dissipate some of the inaccuracies and ambiguities present in existing LCA literature dealing with the global warming mitigation potential of bioenergy technologies. We included all relevant biogenic-CO_2 flows, we applied dynamic emission profiles and climate responses, we included not only WMGHGs but also NTCFs and, finally, we presented both instantaneous and time-integrated Surface Temperature Responses.

Our results indicate with clarity that power generation from cereal straws and cattle slurry can provide global warming mitigation by 2100 compared to current or even future decarbonized European electricity mix in all of the systems and scenarios considered.

Power generation from forest logging residues is an effective mitigation solution only in conditions of decay rates higher than 5.2% a^{-1}. Even with faster-decomposing feedstocks, bioenergy temporarily causes a STR(i) and STR(c) higher than the reference system. Strategies for bioenergy deployment should take into account possible increases in global warming rate, magnitude of temperature anomaly as well as of cumulative radiative forcing.

We envision that this comprehensive assessment will support policymakers in identifying and promoting the bioenergy configurations that are proven to consistently provide climate change mitigation compared to current and future electricity generation mixes.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2016.02.024.

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