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POLICY ANALYSIS

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Heat, Electricity, or Transportation? The Optimal Use of Residual and Waste Biomass in Europe from an Environmental Perspective

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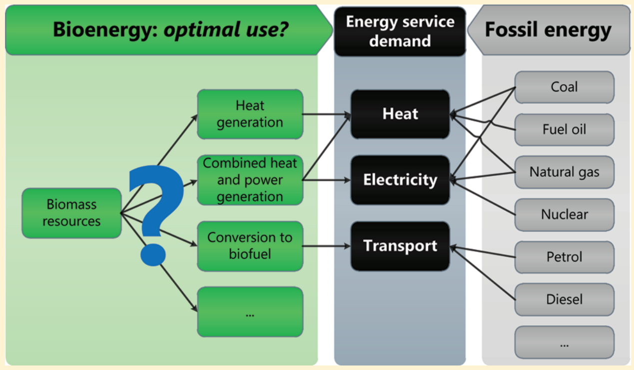
S *Supporting Information*

ABSTRACT: The optimal use of forest energy wood, industrial wood residues, waste wood, agricultural residues, animal manure, biowaste, and sewage sludge in 2010 and 2030 was assessed for Europe. An energy system model was developed comprising 13 principal fossil technologies for the production of heat, electricity, and transport and 173 bioenergy conversion routes. The net environmental benefits of substituting fossil energy with bioenergy were calculated for all approximately 1500 combinations based on life cycle assessment (LCA) results. An optimization model determines the best use of biomass for different environmental indicators within the quantified EU-27 context of biomass availability and fossil energy utilization. Key factors determining the optimal use of biomass are the conversion efficiencies of bioenergy technologies and the kind and quantity of fossil energy technologies that can be substituted. Provided that heat can be used efficiently, optimizations for different environmental indicators almost always indicate that woody biomass is best used for combined heat and power generation, if coal, oil, or fuel oil based technologies can be substituted. The benefits of its conversion to SNG or ethanol are significantly lower. For non-woody biomass electricity generation, transportation, and heating yield almost comparable benefits as long as high conversion efficiencies and optimal substitutions are assured. The shares of fossil heat, electricity, and transportation that could be replaced with bioenergy are also provided.



1. INTRODUCTION

Bioenergy from residual and waste biomass could cover a substantial part of our energy demand while avoiding most of the problems associated with dedicated bioenergy crops.[1−3] Both the scientific community as well as governments have often focused in the past on biofuels for transportation.[4−7] Since biomass resources are limited and can be used to produce alternative energy services, e.g. for heating, electricity generation, or transportation, the question arises which are the optimal uses of different biomass feedstocks from an environmental perspective.

Despite the importance of the question, few studies have made an attempt so far to present a comparison of the use of biomass to provide alternative energy services.[4] The studies that do make such comparisons, e.g., refs 2 and 8−12, are all limited in scope by focusing only on one or a few selected feedstocks, a small number of bioenergy and fossil technologies, or the evaluation with only one environmental indicator.

More comprehensive studies are required to answer the question of the optimal use of biomass appropriately. Such studies should aim at meeting at least the following requirements: first, all potential energetic uses of biomass (heating, electricity generation, and transportation) should be considered. In order to enable fair comparisons the resource perspective must be adapted by comparing alternative biomass uses per unit of biomass input.[4] Second, for each biomass use all relevant established and developing bioenergy technologies should be included. Third, the substitution of fossil technologies needs to be considered, since the environmentally most beneficial use of biomass may depend on the fossil technologies that can be replaced.[2,13] Fourth, the use of bioenergy should be evaluated with different environmental indicators to identify solutions which are beneficial from more than just one perspective.[2,14] Finally, it may be necessary to account for system related constraints, such as biomass potentials, energy demand, and limits to the substitution of fossil energy technologies, in order to provide realistic recommendations.

The goal of this paper was to conduct an analysis for the optimal use of residual and waste biomass in the EU-27 in which

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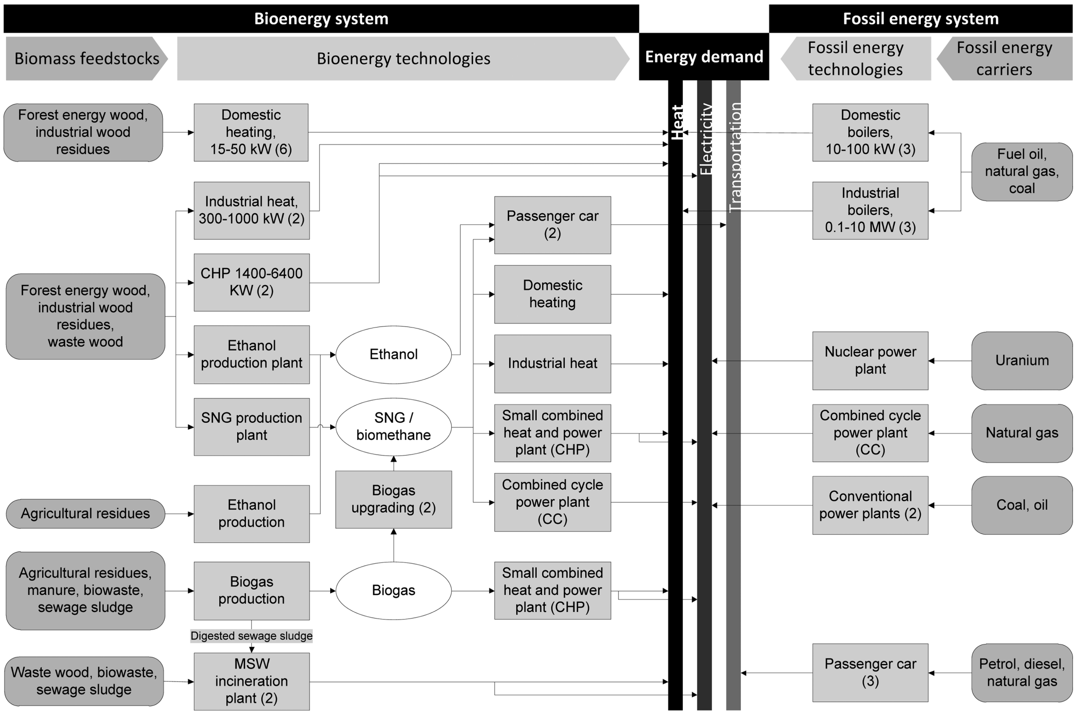

Figure 1. Model of the bioenergy and fossil energy systems used in this study. Numbers in parentheses indicate the number of considered technologies.

we attempt to meet these requirements. It is based on a quantified energy system model including a large set of bioenergy and average fossil energy technologies for substitution. Model optimization is performed for 2010 and 2030 scenarios, which differ with regard to biomass potentials and the use of fossil energy technologies. The optimization is based on technology life cycle assessment (LCA) results for different environmental indicators.

2. MATERIAL AND METHODS

2.1. Life Cycle Assessment. LCA is a method to assess potential environmental impacts caused by products, processes, or activities.[15] The basis for an LCA is a life cycle inventory (LCI) which quantifies all relevant energy and material flows as well as emissions and waste that originate along the life cycle of a product. Environmental impacts are calculated from the LCI and evaluated on the basis of individual impact categories (midpoints) or by normalization and weighting of the latter in form of aggregated damage indicators (endpoints). *Midpoint indicators* considered in this study are the global warming potential (GWP IPCC 100a),[16] ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial acidification, freshwater eutrophication, and terrestrial ecotoxicity from the environmental impact assessment method ReCiPe.[17] As an *endpoint indicator* the ReCiPe single score is used. Additionally, the fossil nonrenewable cumulative energy demand (CED) is considered.[18]

The *function* of the modeled system is to make use of the domestic biomass potentials within the EU-27 energy system. For the comparison of bioenergy technology alternatives we use the input related *functional unit* “1 MJ biomass” (a comparison based on the energy output would not be appropriate[4]).

We assume that biomass is used to substitute energy otherwise provided by fossil energy sources. The *net environmental benefit* of using 1 MJ of biomass to substitute fossil energy services is calculated by subtracting the impacts of the fossil energy technology from the impacts of the bioenergy technology. The amount of avoided impacts from fossil energy technologies depends on the energy services output from 1 MJ biomass input and therefore on the efficiency of the biomass conversion chain.

2.2. Energy System Modeling. *2.2.1. Biomass Feedstocks and Potentials.* Figure 1 shows the selection of bioenergy technologies and fossil energy technologies within our model of the EU-27 energy system. Environmentally compatible potentials of residual and waste biomass feedstocks for 2010 and 2030 are based on a report of the European Environment Agency for the EU-25[19] and data for Bulgaria and Romania.[20] We used the following feedstock classification (subcategories of the original studies are indicated in parentheses): *forest energy wood* (forest residues, complementary felling residues, and stemwood), *industrial wood residues*, *waste wood* (from demolition, packaging, and households), *animal manure* (wet and dry manure), *biowaste* (biological fraction of municipal solid waste (MSW), other agricultural and food processing residues), and *sewage sludge*. The environmentally compatible biomass potentials are shown in Table 1, subdivided into woody and non-woody biomass. Depending on the feedstock, additional efforts may be required to mobilize these potentials and make them available on the market.[19]

2.2.2. Bioenergy Technologies. Feedstock conversion routes, referred to here as bioenergy technologies, for forest energy wood, industrial wood residues, and waste wood include direct combustion to generate heat for domestic heating or the industry and combined heat and power (CHP) generation as well as the production of ethanol and synthetic natural gas (SNG). SNG can subsequently be used for heating, CHP, electricity generation, or transportation, and ethanol is used for transportation (Figure 1).

Agricultural residues, manure, biowaste, and sewage sludge are either fermented to produce biogas or ethanol. If biogas is produced, it can either be used directly in CHP plants, or it can be upgraded

Table 1. Primary Energy Content for Residual and Waste Biomass Potentials in the EU-27 (Based on Refs 19 and 20)

biomass feedstocks	petajoule 2010[a]	2030[a]
woody biomass	*2762*	*2762*
forest energy wood	1896	1771
industrial wood residues	648	690
waste wood	218	301
non-woody *biomass*	*2825*	*2706*
agricultural residues	1206	1206
animal manure	670	670
biowaste	916	788
sewage sludge	33	42
total	*5587*	*5468*

[a] Year.

Table 2. EU-27 Final Energy Demand from Fossil Sources in Our Adaptation (Without Bioenergy) of the Scenarios Today,[23] Reference,[24,25] and Revolution[26a]

sector	unit	Today 2010	Reference 2030	Revolution 2030
heat: households and services	*exajoule*	12.0	11.4	10.3
heat: industrial sector	*exajoule*	8.2	8.7	6.6
electricity	*exajoule*	8.8	10.4	6.3
transport	*10E12 pkm*	4.8	5.5	4.1

[a] Abbreviation: pkm = passenger kilometer. See Figure 2 and the Supporting Information for fossil energy technology use.

to biomethane and used for heating, electricity generation, or transportation. Ethanol is used for transportation. Waste wood, biowaste, and sewage sludge can also be disposed of in a MSW incineration plant. Digested sewage sludge is used for CHP generation in MSW incineration plants.

In order to avoid unrealistic substitutions in the heat sector due to furnace size and temperature level, it was split into the sectors *heat for households and services* and *heat for industrial use*. Only heat from biomass generated in small furnaces (10−100 kW) was allowed to substitute fossil heat for households and services. Only heat generated in large furnaces (>100 kW−10 MW) was allowed to substitute fossil heat for industrial use. Additionally, heat from large furnaces and CHP could be used in district heating networks to deliver heat to households and services. In this case, network losses of 11% were assumed.[21]

Life cycle inventories for all conversion routes including feedstock supply, transportation, and possible pretreatments are taken from the ecoinvent database v2.2.[22] Since not all conversion routes were readily available, additional ones were created wherever possible by modularizing and subsequently recombining parts of the production chain, yielding a total of 173 distinct bioenergy technologies.

2.2.3. Fossil Energy Technologies. The 13 average fossil energy technologies are based on ecoinvent data. Fossil fueled household heating systems include a natural gas boiler (<100 kW), a light fuel oil boiler (10 kW), and an anthracite stove (5−15 kW). Heat for industrial use is provided by natural gas (>100 kW), fuel oil (1 MW), or hard coal (1−10 MW) furnaces. Electricity is provided by average EU nuclear, natural gas combined cycle, hard coal, or oil power plants. Petrol, diesel, and natural gas fueled passenger cars are the transportation alternatives.

2.2.4. Scenarios. In order to evaluate the optimal use of biomass under different circumstances, the final energy demand (Table 2) and its supply by fossil energy technologies (see Figure 2 and the Supporting Information) were quantified in three scenarios. These intend to represent i) *today's situation* (*Today 2010*) based on Eurostat data,[23] ii) a *likely future situation* based on the European Commission's Reference scenario *(Reference 2030)*,[24,25] and iii) a *green future situation* based on the energy revolution scenario *(Revolution 2030)* of Greenpeace and the European Renewable Energy Council.[26]

The use of renewable energies (e.g., biomass, wind, solar, geothermal) is already considered in these scenarios. Thus, in order to be able to optimize the use of biomass, we removed it from the energy supply scenarios and thereby avoid double counting. The resulting energy gap was closed by increasing the use of fossil energy technologies proportionally to their use in each scenario. Consequently, the use of fossil energy in our scenarios is higher than in the original scenarios (Today: 3−13%, Reference: 11−15%, Revolution: 8−48%, see the Supporting Information for details). There are two problems associated with this approach: first, due to the nature of the available statistics individual biomass feedstocks could not be distinguished and thus also biomass from feedstocks not considered in our study, e.g. dedicated bioenergy crops, was removed from the energy supply (which partly explains the higher numbers in the Revolution scenario). Second, the assumption that the additionally required energy is supplied by the same mix of technologies as in the original scenario might be wrong. While this does not qualitatively affect our results for the scenarios Today and Reference, the results for the Revolution scenario should be seen more critically (see 3.4.2 for a discussion on quantitative aspects regarding the substitution of fossil energy).

2.3. Optimization Procedure. The optimization objective was to use biomass to minimize the environmental impacts of the energy system. Additionally, alternative optimization objectives were the maximal production of heat, electricity, and transportation.

The optimization was done in a three-step procedure: first, the net environmental benefits were calculated for all approximately 1500 substitution options, i.e. combinations of bioenergy technologies and replaced fossil energy technologies. Subsequently, these substitution options were ranked according to their net environmental benefits for each environmental indicator. The rankings for the goals "max. heat", "max. electricity", and "max. transportation" were established based on the conversion efficiencies of bioenergy technologies. The selection of substituted technologies and among technologies with the same conversion efficiency was based on net environmental benefits for GWP.

Second, to account for system related constraints, such as biomass availability and use of fossil technologies, a quantitative system optimization model was developed. In the model the substitution options were selected according to their net benefit ranking until either no more biomass was available or no more of a fossil technology could be substituted. Then, the overall system environmental impacts as well as the heat, electricity, and transportation output were calculated.

Finally, Monte Carlo simulation was performed (1000 runs) for the first two steps with hypothetical uncertainties for LCIA

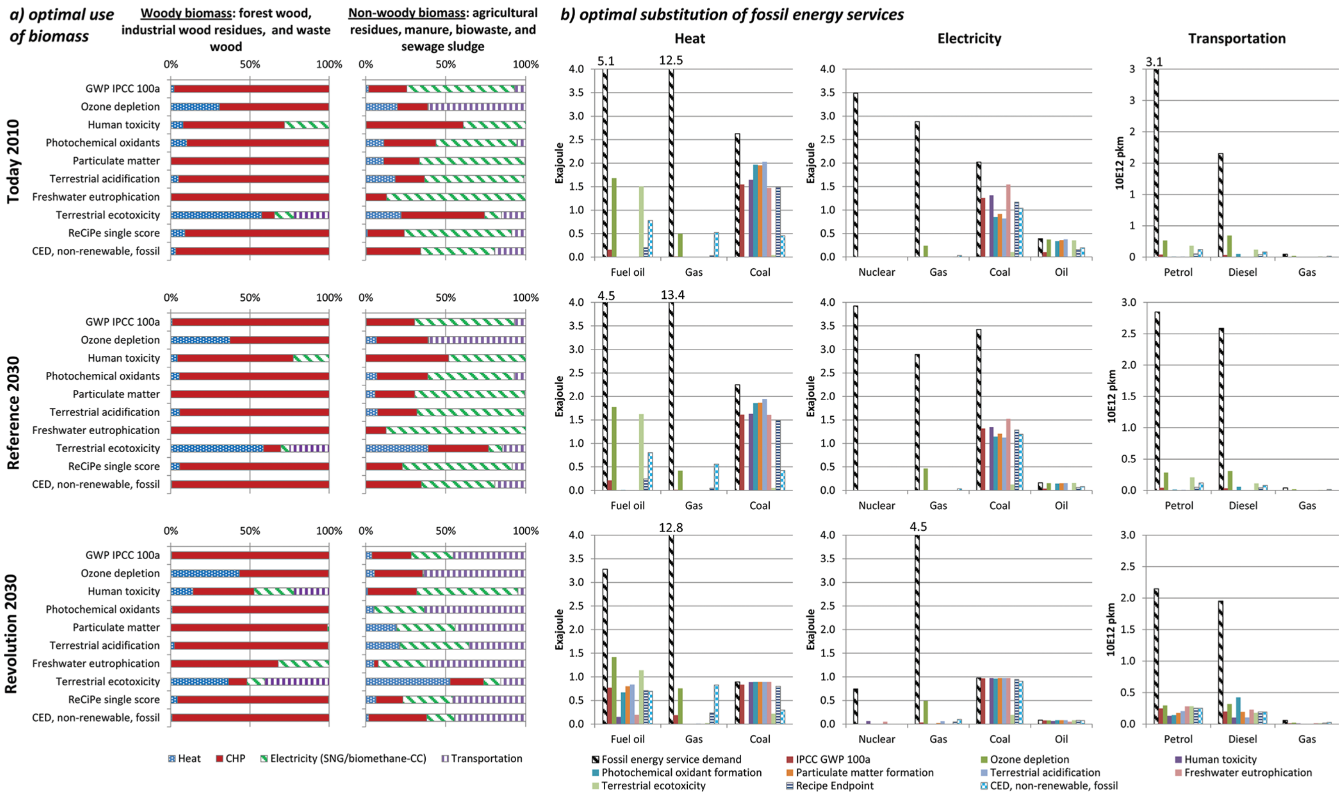

Figure 2. Optimal biomass use (a) and optimal substitution of fossil energy services (b) for different environmental indicators and scenarios. Percentages in (a) indicate the share of biomass potentials that should optimally be used for heating, combined heat and power (CHP), electricity generation from synthetic natural gas (SNG)/biomethane in a combined cycle power plant, and transportation. Values in (b) indicate the demand for fossil energy services (striped bars) and the substitution potential with bioenergy if used optimally (solid bars). Results are based on Monte Carlo simulations with a standard deviation of 0.2 for LCIA values.

results. Technology LCIA results were randomly varied within Gaussian distributions of 0.1−1 standard deviations (i.e., in 95% of all cases the LCIA results deviated less than +−20% and +−200%, respectively, from the original mean values). By introducing this probabilistic component a fundamental optimization bias was overcome, which was that small and statistically insignificant differences in LCIA results determined the ranking of substitution options. The Monte Carlo simulation as implemented here should be seen as a sensitivity analysis aimed at providing "what-if" uncertainty ranges for the combined LCI and LCIA phases to support or question the validity of the results rather than an incorporation of real uncertainties. Results are in the following presented for a standard deviation of 0.2 and its sensitivity is discussed.

3. RESULTS

3.1. Optimal Bioenergy Use and Substitution Choices. Figure 2 shows how the biomass potentials should be used and which fossil technologies should be replaced according to the different environmental optimizations for the three scenarios. There is a general agreement among environmental optimization criteria that *woody biomass* should best be used for CHP generation or to a lesser extent direct heating and substitute heat from coal furnaces and electricity from coal or oil. Results for some indicators (e.g., ozone depletion, terrestrial ecotoxicity) also suggest that fuel oil should be replaced first. The conversion to SNG and its subsequent use for electricity generation in a combined cycle power plant or transportation are less optimal. This remains true also in the Revolution scenario even though a slight increase of the latter uses is induced by the fact that heat and electricity from coal and oil can be completely substituted with only a part of the biomass. Remaining woody biomass is used to substitute heat from fuel oil or natural gas.

The optimal use of the *non-woody biomass* is dominated slightly by the use of biomethane in combined cycle plants for the generation of electricity in the scenarios Today and Reference. Nevertheless, the other uses for heating, biogas CHP generation, or transportation yield almost similar benefits. In the Revolution scenario, due to the complete substitution of coal and oil based electricity and heat, the use of non-woody biomass for transportation dominates.

Despite the observed similarity in patterns there are differences among individual feedstocks (see the Supporting Information): agricultural residues e.g. can be converted to ethanol and for the modeled technologies, the conversion is more energy efficient than the conversion to biogas. Therefore its use for transportation is higher than that of other feedstocks. The use of sewage sludge for CHP generation also remains dominant throughout all scenarios.

3.2. Fossil Energy Substitution Potential. Table 3 shows that the maximal fossil energy substitution potentials are 17−21% for heat, 16−26% for electricity, and 34−45% for transportation, depending on the scenario. If used optimally, residual and waste biomass should replace 6−13% of the heat, 3−18% of the electricity, and 0−15% of the fossil energy demand for transportation, depending on the environmental indicator.

Table 3. Optimal Share of Fossil Energy Services Substituted According to Optimization Criteria

	Today 2010			Reference 2030			Revolution 2030		
optimization criterion	heat	electricity	transportation	heat	electricity	transportation	heat	electricity	transportation
heat	17%	0%	0%	17%	0%	0%	21%	0%	0%
electricity	0%	19%	0%	0%	16%	0%	0%	26%	0%
transportation	0%	0%	40%	0%	0%	34%	0%	0%	45%
GWP IPCC 100a	8%	16%	2%	9%	13%	1%	11%	17%	11%
ozone depletion	11%	7%	13%	11%	6%	11%	13%	9%	15%
human toxicity	8%	15%	0%	8%	13%	0%	6%	17%	6%
photochemical oxidant formation	10%	14%	1%	9%	12%	1%	9%	16%	14%
particulate matter formation	10%	15%	0%	9%	13%	0%	10%	17%	9%
terrestrial acidification	10%	14%	0%	10%	12%	0%	10%	18%	8%
freshwater eutrophication	7%	18%	0%	8%	15%	0%	6%	17%	13%
terrestrial ecotoxicity	8%	5%	7%	8%	3%	6%	8%	4%	11%
recipe single score	9%	15%	2%	9%	13%	2%	10%	17%	11%
CED, nonrenewable, fossil	9%	14%	5%	9%	13%	4%	11%	17%	11%

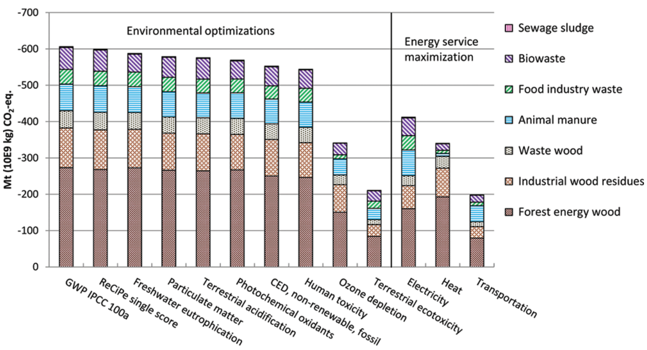

Figure 3. GHG mitigation potential for different optimization criteria and the contribution of biomass feedstocks (reference scenario).

3.3. GHG Reductions for Different Optimization Criteria. Figure 3 shows greenhouse gas (GHG) mitigation potentials according to different optimizations and the role of individual biomass feedstocks. The maximal reductions of approximately 600 Mt CO_2-eq. are obviously achieved if the technology selection is optimized from the GWP perspective. It can be observed that most environmental optimizations lead to GHG reductions close to this maximum. Only a few indicators, e.g. ozone depletion and terrestrial ecotoxicity, result in less optimal solutions from the GWP perspective, which is partly due to the selected direct heating and transportation pathways to substitute fossil energy carriers other than coal. The maximization of energy services output heat, electricity, and transportation all lead to suboptimal results. If all biomass is used only for transportation, the potential GHG savings are reduced by a factor of 3. Note that while woody biomass comprises only about 50% of the primary bioenergy potential (Table 1), it may contribute to approximately 70% of the GHG reductions due to higher conversion efficiencies.

3.4. Sensitivity Analysis. Uncertainties are an important and often unaddressed issue in LCA.[27] There are different sources of uncertainty due to data and modeling choices made in the goal and scope definition, LCI, and LCIA phases.[28] Uncertainties further exist with regards to the choice of substitution options and the quantitative system optimization (biomass potentials, energy demand, and fossil technology use). These uncertainties are addressed in the following through sensitivity analyses (figures are provided in the Supporting Information).

3.4.1. LCI and LCIA. Sensitivity analysis for the *standard deviation of LCIA results* used in the Monte Carlo simulations was performed for values from 0.1 to 1. We observed that the trends presented in this study were usually maintained for standard deviations higher than 0.2, especially for woody biomass. However, as expected, higher LCIA uncertainties led to less clear results as the differences between the individual biomass uses blurred. While for woody biomass the ranking among the biomass uses did not change at higher standard deviations (except for ozone depletion), CHP usually became the dominant optimal use of non-woody biomass. We assume that this is supported by the statistical effect that the selection of specific biomass uses increases with number of technologies available for that use. This is a potential source for misinterpretation, which future modellers should keep in mind.

Sensitivity analysis for a *50% increase of LCIA results of oil based technologies* (for heating, electricity generation, and transportation, e.g. due to future production from oil sands) showed that woody biomass would still be optimally used for CHP generation, but the share of replaced fuel oil would be higher. For non-woody biomass the production of ethanol and biomethane for transportation would become as beneficial as the production of electricity.

3.4.2. Substitution of Fossil Energy Technologies. If *coal could only partly or not at all be substituted* (e.g., due to technological, economic, or other constraints), the use of woody biomass would be most favorable for direct heating and CHP generation and according to some indicators also for transportation.

If *all fossil energy technologies could only be replaced to a maximal degree of 50%*, our recommendations would still be valid for the scenarios Today and Reference. In the Revolution scenario coal could be fully substituted and the leftover biomass would optimally be used for the replacement of fuel oil and transportation, as discussed previously. These analyses emphasize that the selection of optimal bioenergy technologies depends on the quantitative availability of substitution options.

3.4.3. Biomass Availability. The availability of biomass may change in the future due to changed economic (e.g., competition for biomass), environmental (e.g., nutrient recycling), and societal constraints (e.g., acceptance).[3,29] A *50% increase or decrease in biomass availability* did not lead to significant changes of the use of woody biomass. For non-woody biomass it was observed that at low biomass availability the optimal use was heat and CHP production, whereas at high biomass availability the optimal use shifted toward combined cycle electricity generation. In contrast, in the Revolution scenario non-woody biomass was optimally used for combined cycle electricity generation at low and for transportation at high biomass availabilities. The explanation for the behavior between the scenarios can be found in the different use of fossil energy technologies.

3.4.4. Efficiency. To assess the consequences of technological developments in the conversion of woody biomass to fuels, we increased the *conversion efficiency of wood to SNG* from 56%[13,30] to 70%.[31] In spite of a slight increase of the use of SNG for electricity generation, CHP generation remained the optimal use of wood, which is due to its higher overall energy conversion efficiency (85%) and therefore its substitution potential.

The extent to which CHP technologies were chosen during optimizations strongly depended on the ratio of *heat use from CHP*. If *no heat from CHP generation could be valorized at all*, other biomass uses were chosen and the amount of mitigated GHG dropped by 21%. If this factor was ignored during the optimization (i.e., CHP technologies were chosen), the quantity of mitigated GHG dropped by as much as 41%.

4. DISCUSSION

The results show that woody biomass appears to be most beneficially used in CHP, if heat can be used efficiently, or direct heating to substitute heat from coal furnaces, and electricity from coal or oil. The conversion of woody biomass to fuels is the least beneficial, due to low conversion and therefore substitution efficiencies. This stresses that efficient biomass conversion is a key issue for achieving high mitigation effects. Various sensitivity analyses underline the robustness of these results.

While a few studies confirm these findings,[2,32−34] considerable research is ongoing to produce biofuels from woody biomass.[31,35−38] One main driver is the fact that bioenergy policies are mostly focused on biofuels blending targets[39,40] or subsidies for biofuels,[41] while the assessment of net benefits from a feedstock perspective is widely neglected.

For non-woody biomass our optimizations show the highest benefits when used for electricity generation and transportation, depending on the scenario. However, all biomass uses yield environmental benefits in a similar range as long as coal or oil based technologies can be substituted. The importance of the right choice of fossil technology substitution for the net environmental benefit suggests that energy and environmental policies should focus on optimal biomass uses and at the same time provide incentives for the substitution of high impact fossil technologies, e.g. through carbon taxation.

The substitution of natural gas based technologies and nuclear power seems to be the least urgent. However, in light of the recent nuclear catastrophe in Japan a revision of the impact assessment methods for nuclear power should be considered.

We also show that quantitative substitution limits may influence the results. Therefore, country specific recommendations may differ from our EU-27 assessment. We recommend both trans-sectoral net benefit analyses and quantitative context specific analyses as a basis for bioenergy policy development.

Our study shows a considerable agreement among results for different environmental optimizations, which should increase confidence in the recommendations. Nevertheless, the selection of the environmental indicators is ultimately a subjective one, and a different choice of indicators or focus on specific impact assessment methods may lead to other conclusions.

The validity of the results is also limited by the fact that not all relevant technologies were considered, e.g. due to the absence of available inventory data. Not considered were the synthesis of fuels other than ethanol and SNG (e.g., methanol, DME, hydrogen, and Fischer−Tropsch diesel). However, conversion efficiencies related to these technologies are in the same range or lower than to SNG,[42−45] and it is presumed that the conclusions for woody biomass provided here are not affected. On the other hand, certain conversion routes that were not considered may be more efficient than the ethanol and biogas conversion routes, e.g. the production of biodiesel from specific biomass feedstocks such as animal fat and cooking oil and the direct combustion, gasification, or advanced second generation conversion of lignocellulosic biomass such as straw.[11,46,47] These pathways could therefore be preferable to those assessed here. Other neglected early development stage technologies include e.g. direct incineration of sewage sludge for phosphorus recuperation[48] or hydrothermal gasification.[49]

Finally, economic evaluations, which were intentionally excluded to provide a pure environmental perspective, are necessary to find strategies to support the eco-efficient use of biomass. The model presented in this article could be extended to include life cycle cost calculations and determine optimal biomass uses from both economic and environmental perspectives. Several recent studies indicate that the environmental recommendations given in this article align well with the economic performance of bioenergy conversion. Kalt and Kranzl[50] outline for the context of Austria that the most cost-efficient options for reducing GHG emissions using woody biomass are direct heat generation and CHP applications, provided that heat can be used efficiently. In contrast, the abatement cost from synthetic transport fuels from wood can be significantly higher. These findings are confirmed by a study for the Swedish context[51] as well as by Schmidt et al.[52] who additionally consider spatial factors.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information. Detailed data for the bioenergy and fossil energy technologies, the use of fossil technologies, and the optimal use of individual feedstocks as well as our sensitivity analyses. This material is available free of charge via the Internet at http://pubs.acs.org.

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