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Allocation of biomass resources for minimising energy system greenhouse gas emissions

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ABSTRACT

The European Union (EU) energy policy has three targets: supply security, development of a competitive energy sector and environmental sustainability. The EU countries have issued so-called National Renewable Energy Action Plans (NREAP) for increased renewable energy generation. Biomass is stipulated to account for 56% of renewable energy generation by 2020, corresponding to an increase in bioenergy generation from 2.4×10^9 GJ in 2005 to 5.7×10^9 GJ in 2020.

There is uncertainty about the amounts of biomass available in the EU, and import challenges policy targets on supply security and sustainability. We address issues about how, from a technical point of view, the EU may deploy its biomass resources to reduce greenhouse gas (GHG) emissions from energy consumption. We investigate if deployment patterns depend on resource availability and technological development. In situations with adequate biomass availability the analysis suggests that liquid fuel production should be based on agricultural residues. Electricity production should be based on forest residues and other woody biomass and heat production on forest and agricultural residues. Improved conversion technologies implicitly relax the strain on biomass resources and improve supply security.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has identified greenhouse gas (GHG) emissions from energy production as one of the major contributors to anthropogenic climate change [1]. As counter measures national and supra-national initiatives such as the Kyoto Protocol [2] and the European Union Energy Strategy 2020 [3] have been initiated. Binding targets on renewable energy production, e.g. the European Union Renewable Energy Directive (RED) [4], the American Recovery and Reinvestment Act [5], and the Australian Mandatory Renewable Energy Target [6] are set to put pressure on the energy sector to develop cleaner energy technologies and to promote a shift from fossil to renewable energy resources.

Similarly, the European Union (EU) has developed a number of schemes to support renewable energy in general and bioenergy in particular. Schemes apply instruments as import duty relaxation, tax reductions and mandates [7,8]. Also the Common Agricultural Policy (CAP) supports the production of biomass for energy [8]. The European Union biomass action plan from 2005 targeted particularly the use of biomass for heat generation [9] and in recent years liquid biofuels have attracted much attention and raised voices of concern and support [10–15].

The current EU energy policy has three targets: supply security, development of a competitive energy sector and mitigating climate change/improving environmental sustainability. To meet these targets EU countries have issued tangible plans for increased renewable energy generation till 2020 [16]. The so-called National Renewable Energy Action Plans (NREAP).

Biomass is a cornerstone of the NREAPs and is stipulated to account for 56% of renewable energy generation by 2020 [16]. This corresponds to an increase in bioenergy generation from 2.4×10^9 GJ in 2005 to 5.7×10^9 GJ in 2020. There is, however, a significant uncertainty about the amounts of biomass available in the EU for energy purposes [17], and imports from outside the EU challenges the policy targets on supply security and sustainability.

In the light of the uncertain biomass potential, a paramount question for the EU is how to deploy its own limited biomass resources in the energy sector. The target is to, on the one hand, meet

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Nomenclature

Abbreviations

CAP	Common Agricultural Policy of the European Union
EU	European Union
GHG	Greenhouse gases
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LHV	Lower heating value
LP	Linear programming
NREAP	National Renewable Energy Allocation Plan
RED	Renewable Energy Directive of the European Union
SQP	Sequential quadratic programming

Model parameters

x	Amount of biomass resource allocated to energy service, variable, model solutions
c	GHG emission cost of allocating a unit of biomass resource to energy service, variable, Table 1
g	Biomass conversion efficiency, variable, Tables 1 and 4
S	Biomass resource availability, variable, Table 2
D	Energy service demand, fixed, Table 3
a, b, d	Defining the non-linear form of the objective function, fixed, Fig. 2

Subscripts

i	Biomass resource: 1) Agricultural residues, 2) Forest residues, 3) Energy crops, 4) Imported wood
j	Energy service: 1) Heat, 2) Electricity, 3) Liquid fuel

the obligations in the Renewable Energy Directive and simultaneously meet the energy policy targets on GHG emission abatement and supply security.

In this paper we address the question of how, from a technical point of view, the EU may best deploy its biomass resources to reduce GHG emissions from energy consumption, while as far as possible using them towards projected energy needs in various uses. We investigate further the question if deployment patterns depend on resource availability and technological development. Finally we analyse if either of these may technically allow for higher ambitions than current policies reflect.

A number of authors have shown that constrained resources can have an important impact on minimising the total GHG emissions from an energy system. These studies demonstrate that a naive policy approach focusing on technical GHG emissions for specific technologies will not necessarily result in the minimization of the total GHG emissions for a system.

In minimising the total GHG emission from a hypothesised energy system, while balancing the requirements for security from the demand side with stability characteristics on the biomass production side, Tan [18] found an optimal allocation of two competing biomass resources to energy services. It is shown that stability characteristics of individual resources can override technical GHG performance of the same resources in the development of robust energy planning.

For the Australasian region Graham et al. [19] analysed the competition for biomass between and within the stationary and transportation sectors and optimised resource allocation. Preliminary results show that biomass as a whole increased its penetration into the energy market. Qualitative shifts appear over time due to changes in biomass availability, carbon credit prices and technological development. The authors conclude that currently most biomass should be allocated to electricity production and road transport but from 2025 and onwards an exponential growth in aviation fuels and decline in biomass allocated to electricity and road transport is expected.

Tan et al. [20] show for a model energy system that regional differences in land availability and biomass characteristics impact optimal allocation of biomass to conversion technologies and trade. It is found true even when technological conversion parameters are identical between regions.

Contrary to the above examples, which are based on single-objective mathematical optimisation techniques, Steubing et al. [21] combine constrained biomass resources, LCA and technical ranking of biomass to energy pathways to determine the optimal use of biomass for energy in the EU under a range of different environmental objectives. The ranking procedure yields a variety of mixed strategies for optimal biomass use depending on which environmental parameter (e.g. global warming, terrestrial acidification or non-renewable energy use) is targeted.

Considering the limited biomass resources Kwon and Østergaard [22] analyse how increasing constraints on biomass availability change the configuration and behaviour of a simulated Danish energy system based on 100% renewable resources. They find than in most situations biomass constraints should lead to reduced heat generation from biomass rather than reduced electricity generation.

In contrast to previous studies we take the position that the amount of biomass available for energy purposes is uncertain. Furthermore we assume that GHG emissions associated with exploitation of a unit of biomass is not constant but dependent on the proportion of available biomass exploited. We analyse, from a technical point of view, how the available biomass is best allocated to satisfy projected needs for various energy services. The analysis focuses on the EU, its targets on renewable energy generation and incorporates careful attention to its potential within-EU supply of own primary biomass resources. We also investigate how the development of existing technologies till 2020 affects optimal biomass use. Although forecasts on future energy technological development have a long history of failure [23], technology development may be a game-changer for optimised biomass allocation strategies.

2. Materials and methods

This analysis builds on a conceptual model of an energy system generating bioenergy in the EU as stipulated in NREAP by 2020 (Fig. 1). Here we focus on the use of solid biomass produced in the EU as well as ethanol produced in compliance with article 21.2 in the Renewable Energy Directive [4], so-called 2nd generation bioethanol. These sources are expected to contribute more than 70% of the bioenergy generated in 2020. Biomass resources for 1st generation bioethanol and biodiesel are disregarded here as these are based predominantly on traditional food crops or food wastes (e.g. used cooking oil).

The problem is mathematically formulated as a generalised network and solved as a multi-commodity flow problem [24] with a nonlinear objective function and linear constraints.

$$\min f(x) = \sum_{i=1}^{i} \sum_{j=1}^{j} x_{ij} c_{ij}(x_{ij}) \, \forall i,j, \quad (1)$$

where x_{ij} is the amount of biomass from resource i allocated to energy service j, and c_{ij} is the greenhouse gas emission in kg CO_2

equivalents associated with the allocation of 1 GJ biomass from resource i to energy service j.

Subject to equality constraints

$$\sum x_{ij} g_{ij} = \sum D_j \forall i, j, \quad (2)$$

ensuring that demands for energy services are met. g_{ij} is the efficiency of which resource i is converted to energy service j, $0 < g_{ij} \leq 1.08$. The highest conversion efficiency assumed in this analysis is 108% based on LHV, cf. Table 4.

Subject inequality constraints

$$\sum x_{ij} \leq \sum S_i \forall i, j, \quad (3)$$

ensuring that biomass resources are not over-exploited. S_i is the amount of biomass resource i available for energy purposes.

Subject to non-negativity constraints

$$x_{ij} \geq 0 \quad \forall i, j. \quad (4)$$

Supply-cost curves for biomass resources as reported by Haq [25], de Wit et al. [26], and Newes et al. [27] exhibit a non-linear shape, of increased unit costs with increasing supply. This reflects that marginal costs increase as resources of lower quality or more difficult to get at, are being targeted. Supply costs of biomass are a composite of costs for collection, transportation, machinery and fuel, labour and land [25]. Several of these have implications for the GHG emissions of the extraction process itself. Jäppinen [28] show under Finnish conditions that GHG emissions per unit of wood energy supplied increase with the amounts of wood supplied. These findings relate specifically to GHG emission attributable to truck transportation. It is reasonable to assume that GHG emissions associated with biomass use (supply–GHG emission curves) will exhibit an exponential development with increased exploitation of the available resource.

Similar patterns are found in oil extraction, where exploration of unconventional oil resources results in higher GHG emissions than conventional sources [29,30]. When consumption converges towards a production limit of a finite resource more radical methodology or less accessible sources must be exploited with higher GHG emissions as result. Consequently $c_{ij}(x_{ij})$ is expressed as an exponential function:

$$c_{ij}(x_{ij}) = c_{ij,\text{fossil displacement}} + a c_{ij,\text{extraction}} e^{b\left(\sum x_{ij}/S_i\right)} + (1-a) c_{ij,\text{extraction}} e^{d\left(\sum x_{ij}/S_i\right)}. \quad (5)$$

The optimisation problem is solved using a sequential quadratic programming (SQP) algorithm in MatLab (R2011a). SQP is a numerical method for solving constrained non-linear optimisation problems. The objective is solved through a sequence of subproblems, each solving a quadratic model of the objective subject to a linearization of the constraints [31].

2.1. Data

Parameters included in the mathematical model are conversion efficiencies and GHG emissions for different pathways from solid biomass to energy service (Table 1). Data are calculated from recent analyses from the Joint Research Centre of the European Commission [32] and Wihersaari [33]. Data are considered valid for current average EU technologies.

We incorporate an attention to supply security in the form of a penalty GHG emission attributed to imported biomass. Given the objective function, the effect is to avoid import if not necessary to meet demands at given emission levels. Furthermore, when imported biomass is used it is assumed to have same technical characteristics as wood. Biomass imports to Europe predominantly constitute wood [34]. As we shall see, import will play a small role in this technical analysis.

The exponential nature of supply–GHG emission curves for biomass resources is a delicate interplay between e.g. biomass source, location, annual variations, and technological level, and is not known precisely. This paper does not specifically address this issue, but apply approximates based on the exponential shape of supply–GHG curves for other resources. The initial point of supply–GHG emission curves is given by the values presented in Table 1. The curvature of the supply–GHG emission curves is estimated by analogy to oil exploration. Literature reports GHG emissions from the exploration of unconventional oil resources as being 152–893% of those from conventional resources [29,30,35,36], with a majority of values between 200 and 400%. By analogy we assume a curvature of supply–GHG emission curves resulting in an increase of 300% above of the initial point once fully exploited (Fig. 2). Exponentiality applies to the part of GHG emissions attributable to extraction. Emissions from combustion or displacement of fossil resources are unaffected by the proportion of biomass utilisation. These considerations particularly relate to Eq. (5), and was implemented with additional parameters for the objective function, $a = 0.995$, $b = -0.01$ and $d = 6.0$, based on the analogy to petroleum extraction. This ensures the assumed relation between biomass exploitation and GHG emissions illustrated in Fig. 2, and also that the objective function represents a convex set.

2.2. Biomass potential

Biomass availability is paramount to the deployment of more bioenergy in the European energy supply. There is, however, uncertainty about the biomass amounts available. A recent review of European bioenergy resources [17] demonstrates the uncertainty about the amount of biomass available for energy production in the future. The review identifies three major sources of solid biomass: Agricultural residues, forest residues and dedicated energy crops. Energy crops may comprise a variety of crop types from traditional food crops (e.g. wheat or rape seed), herbaceous lignocellulosic crops (e.g. grass) to tree species in shorter or longer rotation (e.g. willow, poplar or eucalyptus). Due to the uncertain nature of future energy crop production we assume energy crops grown to produce solid biomass to be of woody species. In this study biomass constraints are based on the range of estimates for 2020 of these three sources as reported by [17] (Table 2).

The estimated biomass potentials are derived from a number of independent references [17]. The resources themselves are, however, not independent from each other. There is, in principle, a trade-off between agricultural residues and energy crops. Energy crops are typically designated to degraded land or land liberated from agriculture. As such a high amount of energy crops, everything else equal, comes at the expense of a high amount of agricultural residues. While all scenarios are considered possible, scenarios with high amounts of agricultural residues and energy crops (high – × – high) are less likely to occur than scenarios with lesser amounts of one or either resource.

If import is required to meet the demand for energy we assume the imported biomass to be wood as wood or wood derived products make up the bulk of biomass imported to the EU [37]. Agricultural residues are only to a very limited degree traded globally and the trade is dominated by palm nut shells [34]. In this analysis imported biomass is not subjected to constraints in quantity.

Table 1
Conversion efficiencies and GHG emissions from different technological pathways from solid biomass to energy service. Conversion efficiencies indicate the number of units of heat, electricity or ethanol produced from one unit of biomass (LHV). GHG emissions indicate the amount of non-renewable GHG emitted in association with production, extraction and processing of biomass to heat, electricity or ethanol. Data are based on analyses from the Joint Research Centre of the European Commission [32] and Wihersaari [33].

	Resource…	Agricultural residues			Forest residues			Energy crops		
	…to production of	Heat	Electricity	Fuel	Heat	Electricity	Fuel	Heat	Electricity	Fuel
Conversion efficiency ($GJ_{product}\ GJ_{biomass}^{-1}$)		0.85	0.29	0.42	0.85	0.32	0.34	0.85	0.32	0.34
GHG emission (kg CO_2 eq $GJ_{biomass}^{-1}$)	Production							5.07	5.07	5.07
	Collection	1.29	1.29	1.29	1.70	1.70	1.70			
	Transport	0.26	0.26	0.26	0.30	0.30	0.30	0.30	0.30	0.30
	Processing			1.56			4.57			4.57
	Distribution			0.65			0.52			0.52
	Extraction and processing total	1.55	1.55	3.76	2.00	2.00	7.09	5.37	5.37	10.46
	Fossil displacement	−52.01	−64.22	−29.99	−52.01	−70.86	−24.28	−52.01	−70.86	−24.28

2.3. Bioenergy generation

Quantification of the energy demand builds on NREAP projections on energy services generated from biomass in 2020 [16] to meet the requirements in the Renewable Energy Directive (Table 3).

2.4. Technology development

Energy technologies evolve constantly and although projections may fail the longevity of energy facilities and infrastructure demands a critical view upon the options, improved technologies may provide. Increased conversion efficiencies affect the amount of biomass required to meet a given energy service as well as the GHG emissions associated with doing so. As such technological development ties into both supply security and climate change mitigation.

Permutations are performed with a set of alternative conversion efficiencies (Table 4) and derived GHG emissions. Data build on technology reviews and projections from the International Energy Agency [38], Danish Energy Agency [39], and DONG Energy [40].

3. Results

By construction, all the results shown represent scenarios that meet the NREAP production target (Table 3) under various biomass constraints (Table 2).

The main result of the analysis is presented in Fig. 3. The graph shows the amount of agricultural residues, forest residues and energy crops exploited in the EU in GJ (on LHV basis). When imported biomass is required to cover a balance the graph shows the total amount of biomass required.

3.1. Allocation with resource constraints and slacks

The EU as a whole would, in most scenarios, be capable of supporting bioenergy generation from solid biomass by 2020 as stipulated in NREAPs based entirely on its own resources. Only when the potential of two or all three biomass sources fall in the low end of the range import is required and self-sufficiency and supply security is challenged.

In a situation with adequate potential of all biomass resources the general recommendations - based on this technical optimisation to minimise GHG emissions – are fuel production based on agricultural residues, electricity production on forest residues and other woody biomass and heat production on forest and agricultural residues. These results largely corroborate findings from other research [21,41–43].

Also with less favourable biomass potentials it is optimal to base electricity production on wood biomass unless wood resources become so constrained that they cannot meet the demand for electricity.

3.2. Technology development

Optimisations run under assumptions of improved conversion technologies (Table 4) but subject to the same resource constraints as above yield different allocation strategies (Fig. 4). Improved conversion technologies implicitly relax the constraints on resources. Although imports cannot be avoided in situations, where all three resources are heavily constrained, the amount required is significantly lower and supply security correspondingly improved. We note that while still present in a number of optimal strategies the need for energy crops is also significantly reduced. Given the assumptions made on improved technology (Table 4), the results do not imply a fundamental qualitative shift in the configuration of the energy sector. No biomass resource or conversion pathway falls out of the optimised strategies. Optimal allocation strategies are still mixed, however not to the same degree as above.

3.3. Slack resources and renewable energy ambitions

A number of the scenarios analysed above find that there might be additional biomass resources available also after the RED targets are met. From a technical point of view the EU could

Table 2
Biomass resource availability in the EU by 2020. Three supply scenarios (low, medium and high) are identified for three different biomass resources (residues from agriculture and forestry, and dedicated energy crops). Amounts refer the lower heating value (LHV) of the biomass. Data are based on Bentsen and Felby [17].

Resource	Quantity (10^6 GJ yr^{-1}) (LHV)		
	Low	Medium	High
Agricultural residues	900	1286	1672
Forest residues	431	3166	5900
Energy crops	783	2787	4790

Table 3
Stipulated energy generation from solid biomass by 2020 to meet the targets in the EU Renewable Energy Directive. Based on Ref. [16].

Energy service	Quantity (10^6 GJ yr^{-1})
Heat from solid biomass	3230.0
Electricity from solid biomass	558.0
2G bioethanol	30.4

Table 4
Improved biomass conversion efficiencies attainable by 2020. Data build on projections and evaluations by the International Energy Agency, the Danish Energy Agency and Sander et al. [38–40].

Resource…	Agricultural residues			Forest residues			Energy crops		
… to production of	Heat	Electricity	Fuel	Heat	Electricity	Fuel	Heat	Electricity	Fuel
Conversion efficiency ($GJ_{product}\ GJ_{biomass}^{-1}$)	1.02	0.33	0.46	1.08	0.47	0.37	1.08	0.47	0.37

be in a position to pursue higher ambitions than laid down in the RED. Assuming that there by 2020 is a medium potential from all three biomass sources, and the EU is expected to meet all of the projected ethanol consumption with 2nd generation bioethanol the model suggests that avoided GHG emissions could be increased, however only marginally (Fig. 5).

Again assuming a medium potential from all three biomass sources, the model suggests that, the EU would be able to almost double the amount of avoided GHG emission. Such benefits do, however, not come through higher ambitions for biofuels. Minimising GHG emissions from the use of any slack resources show that all should be allocated to electricity production

Technical development also has an impact on the total GHG emission from the system. In the medium-medium-medium scenario (Fig. 5) improved technology may increase the amount of avoided GHG emissions with 2% compared to current technology (in Fig. 5, the second set of bars compared to the first set of bars counted from left).

4. Discussion

4.1. Allocation with resource constraints and slacks

The analysis suggests that the EU, from a technical point of view, in most of the potential supply scenarios, is capable of meeting the 2020 targets on bioenergy with its own biomass resources. Compared to current import of bioenergy, these results illustrate the difference between a technical feasibility and allocation analysis like the present, and the resulting pattern on a market (a market model), where resources are traded freely. The use of imports is driven by their lower price and self-sufficiency is not necessarily an issue for the individual agent.

The results also demonstrate the effect that increasing GHG-emission with increasing exploitation degree has on allocation patterns. Exploiting a constrained biomass resource fully can be an expensive solution in terms of GHG emissions. In the scenarios treated here this is particularly visible in the trade-off between the utilisation of forest residues and the use of energy crops. From a conversion technology point of view they are assumed identical, but dedicated energy crops have larger GHG emissions per unit of biomass than residual biomass from forest operations. Nevertheless energy crops have a role to play in the optimised allocation strategies even when the forest resource is not fully exploited. The same effect is visible when in one case imports are used for fuel services in spite of slack energy crop resources (the low–low–high scenario in Fig. 3).

This analysis illustrates the trade-offs between resource availability and optimal resource allocation to energy services. Joelsson and Gustavsson [44] demonstrated in a similar manner, with the Swedish energy supply as case, how availability constraints on the fossil resources influence the performance of the fossil reference

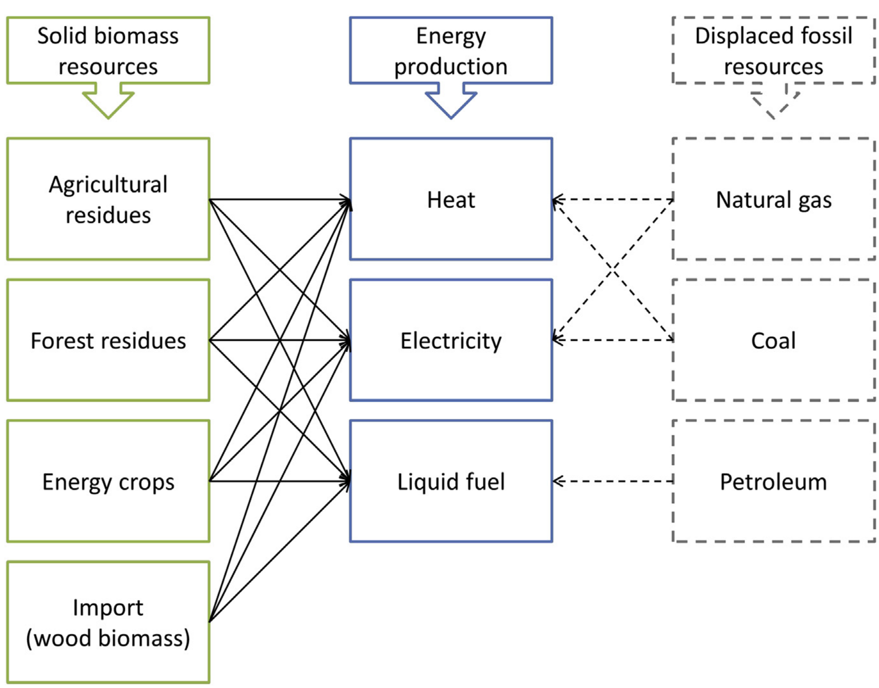

Fig. 1. [Suggested size: 1 column/9 cm]. Network representation of the model energy system analysed. Three domestic sources of biomass (residues from agriculture and forestry and dedicated energy crops) supplemented by import, when necessary, support the production of heat, electricity and liquid fuel according to NREAP projections. Correspondingly fossil resources (natural gas, coal and petroleum) are displaced.

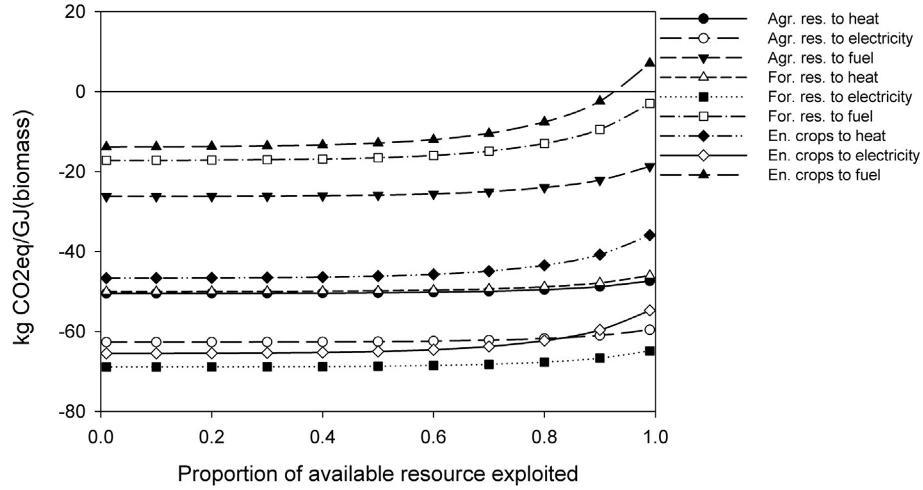

Fig. 2. [Suggested size: 1.5 column/14 cm]. GHG emissions for bioenergy pathways in the EU. GHG emissions are assumed proportional to the ratio between available and exploited biomass resource, but independent of the absolute amount of biomass used.

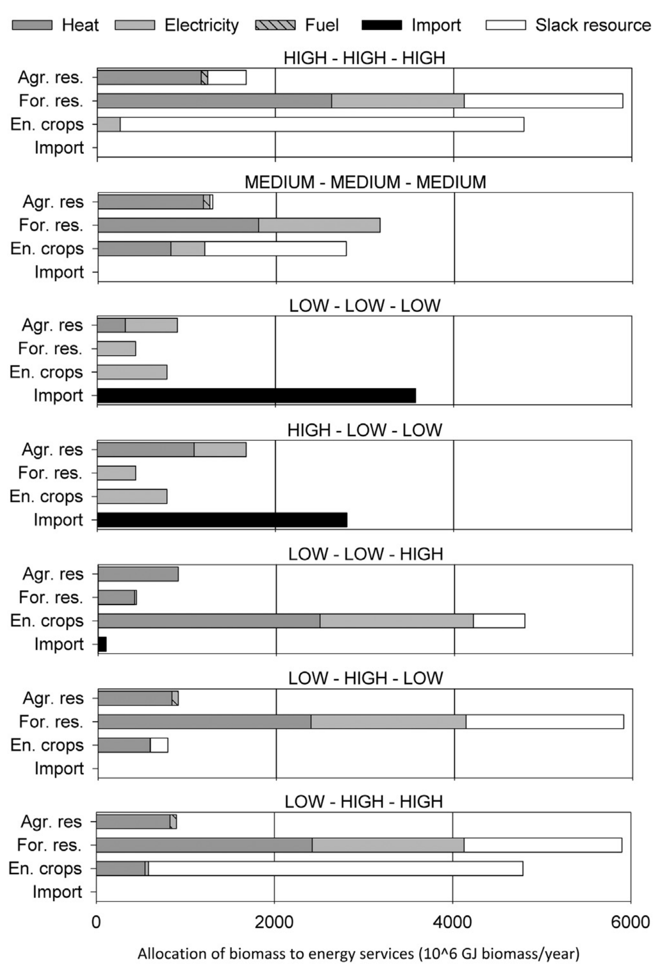

Fig. 3. [Suggested size: 1 column/9 cm]. Optimal allocation of EU produced biomass to energy. Agricultural residues (Agr. res.), forest residues (For. res.) and energy crops (En. crops) allocated to heat, electricity or liquid fuel production to minimise GHG emissions and avoid biomass import under different biomass constraints. 7 out of 27 potential scenarios are presented, which cover the range of supply scenarios analysed in this paper. Model results for all scenarios are presented in Appendix. The header over each pane indicates the level of biomass potential as presented in Table 2.

system to which increased biomass is compared. Increasing constraints on oil and gas divert energy generation to the more CO_2 intensive coal, and in turn increase the benefits of a transition to various forms of bioenergy.

4.2. Technology development

The study shows how technology development relaxes the strain on biomass resources and the subsequent impacts on optimal resource allocation. Similar findings are shown by Joelsson and Gustavsson [44]. Technology development, however, is not confined to biomass conversion technologies. Improved conversion technologies for fossil resources or changed consumption patterns also affect the optimal allocation of biomass. In 2011 the US experienced reduced GHG emission from electricity generation caused inter alia by a shift from coal to shale gas [45]. This change reduces the amount of GHG emissions avoided by displacing fossil resources with biomass and shift focus for biomass use further from electricity generation to other purposes.

4.3. Slack resources and renewable energy ambitions

As a whole the EU ambitions on renewable energy deployment are high compared to other regions. For the transport sector, however, the ambitions on advanced biofuels are somewhat lower. Of a projected consumption by 2020 of 298 $\times$ 10^6 GJ bioethanol/ETBE, 30.4 $\times$ 10^6 GJ or 10% are assumed 2nd generation ethanol/ETBE. 74 $\times$ 10^6 GJ (25%) are expected to be imported. Biodiesel use is projected to 890 $\times$ 10^6 GJ by 2020, with 71 $\times$ 10^6 GJ (8%) as '2nd' generation (based on waste material). A 235 $\times$ 10^6 GJ (26%) is expected to be imported. In comparison the US Energy Independence and Security Act [5] sets a 2022 target of 136 billion litres ($\sim$2900 $\times$ 10^6 GJ) of biofuel for transport in 2022. 80 billion litres ($\sim$1700 $\times$ 10^6 GJ) or 59% are stipulated to come from advanced biofuel production, not based on corn starch.

The results presented here, that slack resources are best used to minimise GHG emissions through additional electricity production corroborate the findings of Steubing et al. [21] and demonstrate that unconstrained optimisation with the objective to minimise GHG emission yield similar results as ranking different pathways on technical performance. While technical

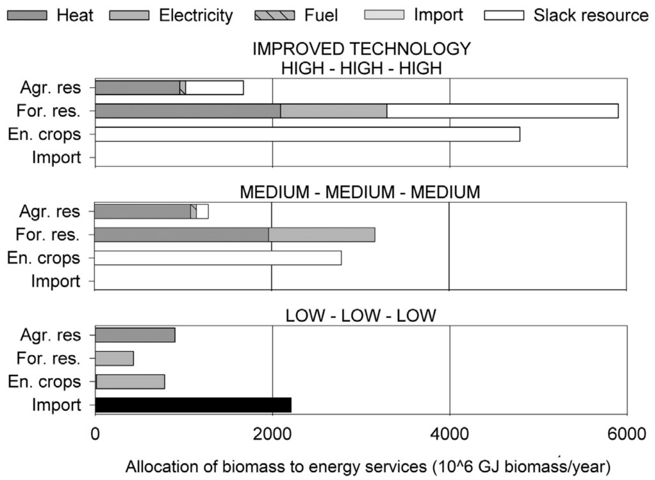

Fig. 4. [Suggested size: 1 column/9 cm]. GHG optimised allocation of biomass to energy with improved conversion technology. The impact of technology improvements is illustrated for three biomass availability scenarios. The header over each pane indicates the level of biomass potential as presented in Table 2.

optimisation with the purpose of reducing GHG emissions disfavour the use of additional biomass for fuel production, other aspects could suggest otherwise. The EU transport sector exhibits significant increases in GHG emissions in contrast to heat and electricity production [46], and addressing the transport sector could have an important symbolic value. This, possibly in combination with low EU ETS prices could call for higher ambitions for biofuels. Supply security valued above GHG emissions could also favour biofuel production over electricity production. In 2009 the EU import dependency of solid fuels amounted to 41.1% as compared to 84.1% for crude oil [47].

The positive effect of technology development on GHG emissions is dependent on resource constraints. The positive effect in the medium–medium–medium scenario is limited. In the low–low–low scenario the model finds that technology improvement increases the amount of avoided GHG emission with 34% (not shown in the graph). This relates to the non-linear form of supply–GHG emission curves (Fig. 2) and to the strain put on available biomass resources. More exponential curves and more strain on resources emphasise the benefits of relaxing the strain through technological development and implementation.

4.4. Method, caveats and future research

Friedman [48] distinguishes an economic from a technological problem as a problem where scarce means are used to meet alternative ends. If means are not scarce there is no problem. If means have only one end it is a technological problem. Within that framework this paper treats a technological problem. The absence of economics in this analysis has its benefits and limitations. By excluding economic considerations we treat the underlying mechanics of an energy system without the 'noise' potentially derived from economic prioritization. The physical and technical constraints of a bioenergy system (e.g. achievable conversion efficiency and photosynthetic efficiency) are more fundamental and permanent features of the system, than fluctuations in economic factors (income, factor costs, and political decisions on investments) driving supply and demand. On the other hand the lack of economic aspects to some degree detaches the analysis from a reality, where political prioritization, protectionism and trade policy (e.g. the Russian export ban) and the basic dynamics of the markets may support solutions that are non-optimal from a technical point of view.

Economic optimisation models are in fact also widely used in bioenergy policy evaluations [19,49–51]. To mention just a few more recent ones, Graham et al. [19] build a resource and demand constraint least cost model solved as a LP-problem. Also

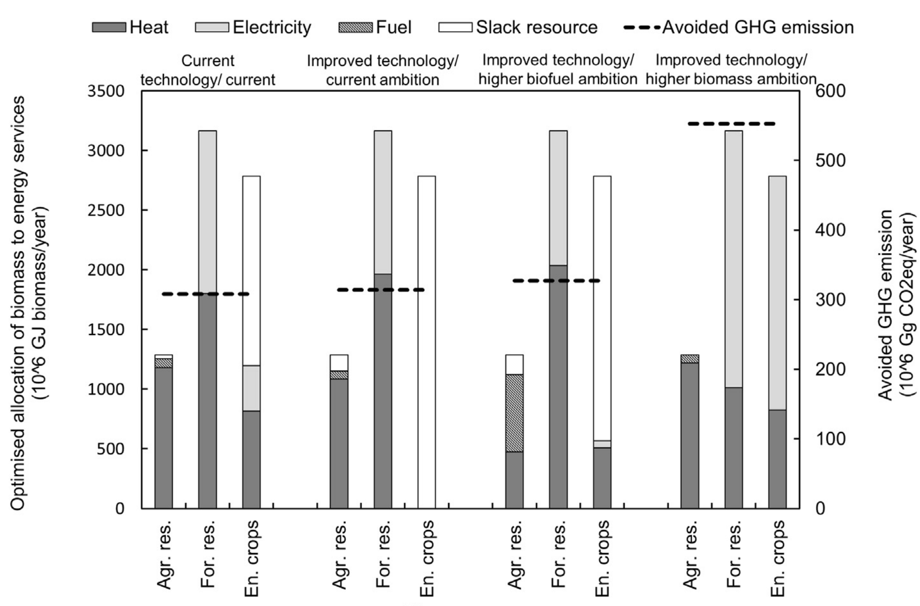

Fig. 5. [Suggested size: 1.5 column/14 cm]. Technically optimal allocation of slack biomass resources to energy. Illustrated for the medium-medium-medium scenario. First set (3) of bars represent current technology applied to meet bioenergy ambitions according to NREAP (equal to Fig. 3, first row, second pane). Second set represents improved technology applied to meet NREAP ambitions (equal to Fig. 4, first row, second pane). Third set represents improved technology applied to meet an ambition of all bio-ethanol demands based 2nd generation ethanol. Fourth set represents improved technology applied to meet an ambition of maximising avoided GHG emissions with slack resources after satisfying the NREAP ambitions.

Gielen et al. [51] and the European Environment Agency [49] apply a least cost procedure in their model. With Greece as a case Papapostolou et al. [52] demonstrate how the cost of producing energy crops influence the economically optimal allocation of biomass to energy. In that study biomass constraints are expressed in the form of constraints to the allocation of land to dedicated energy crop production. Applying cost minimisation in a higher geographical resolution Callesen et al. [53] analyse how various constraints on e.g. food production or landscape values affect optimal allocation of agricultural land to energy production.

Modellers face a significant trade-off between simplicity and tractability versus coverage and completeness. Increasingly complex models may improve the coverage of an analysis but at the expense of increased uncertainty as agents' decisions and actions may not be rational [54]. On the other hand basing decisions on over-simplified models may lead to sub-optimal strategies [50]. Modeller perspective contributes to ambiguity between results on bioenergy systems. The top-down perspective applied in economic or integrated models often yield results contrasting with those from bottom-up models e.g. life cycle assessment (LCA) or technical analysis [55], and direct comparison between results from different families of models is impeded.

LCA is used in a number of studies to select the best use of biomass for energy purposes [21,41,56,57]. LCA is predominantly used for scenario analysis and not for mathematical programming as explored here. LCA does not in itself specify optimal solutions, but attempts have been made to combine LCA and mathematical programming [58], also on energy systems [59].

Here we apply a simple bottom-up model, which is capable of demonstrating a number of general aspects of constrained biomass resources when addressing the technically optimal allocation of biomass for energy with an aim to mitigate climate change. The model has its merits in provoking general thoughts on the balance between available resources and stipulated goals of biomass based energy and energy security, rather than informing specific decisions on biomass use.

Such approaches are, however, also common in the literature on energy systems. Tan [18] approaches optimal resource allocation in a somewhat similar way as here. Tan formulate a supply and demand constraint linear programming (LP) model to find an optimal allocation of two competing biomass resources to energy services under variable risk profiles.

Addressing the transportation sector Pekala et al. [60] study a conceptualised energy supply system under Polish conditions and use LP to solve a network problem with the objective to minimise fuel imports subject to land availability and GHG emission constraints.

Models like the present are of course open to a number of improvements, which could improve their coverage and the type of questions they can address. As shown in this analysis an exponential nature of GHG emission-supply curves has a significant impact on the optimal use of biomass. The specific non-linear form of such curves probably is a delicate interplay between i.e. biomass source, location, annual variations, and technological level. We do not specifically address this question here, but can only recommend further work on this issue.

Furthermore, the analysis has been undertaken for EU totals, but without attention to the large geographical variation in where these biomass resources are and will be used. In particular, there are countries with large biomass resources, which may rely on e.g. nuclear infrastructures to provide the major part of their electricity. Thus, improving the spatial specificity may also reveal new patterns of interest emerging at e.g. the national level.

5. Conclusions

This paper addresses the question of how, from a technical point of view, the EU may deploy best its biomass resources to reduce GHG emissions from energy production. We have developed a bottom-up optimisation model of a conceptualized energy supply for the EU for year 2020.

Biomass, however renewable, is a constraint resource that should be managed carefully to maximise the utility gained. Furthermore the amount available for energy production is highly uncertain, depending on the origin of the resource and on alternative uses. We find that all GHG optimized biomass allocation strategies are mixed, meaning that a number of different biomass resources and conversion technologies must be mobilized to meet the increasing demands for bioenergy. In situations with adequate supply potential of biomass resources the general recommendation, in order to minimise GHG emissions, is that liquid fuel production should be based on agricultural residues, electricity production on forest residues and other woody biomass and heat production on forest and agricultural residues. Also with less favourable biomass potentials our model suggests it optimal to base electricity production on wood biomass unless wood resources become so constrained that they cannot meet the demand for electricity.

A central message from this study is that care should be taken not to overexploit single biomass resources in the pursuit of lower GHG emissions. Although utilisation of residue biomass should be prioritised over dedicated energy crops, the best overall GHG performance is found, when the strain on the total biomass resource is spread over different types of resources. This issue becomes more pronounced with increasing scarceness of biomass resources.

If biomass availability allows the EU to set higher ambitions on bioenergy we show that, from a technical point of view, the model suggest that any slack resource be allocated to electricity production in order to maximize the fossil GHG emissions avoided.

A number of the technologies available for biomass conversion must be considered as immature. Particularly within bio-chemical conversion huge progress in efficiency must be expected. This analysis demonstrates that improvement of biomass conversion technologies can relax the strain on biomass resources and not only improve the overall GHG performance of bioenergy production, but also improve supply security.

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Appendix A. Optimisation model solution to the 27 biomass supply scenarios.

Biomass availability			Optimised allocation of biomass resources to energy production									
Agr. res.	For. res.	En. crops	Agr. res.			For. res.			En. crops			Import
			Heat	Electricity	Fuel	Heat	Electricity	Fuel	Heat	Electricity	Fuel	
10^6 GJ												
900	431	783	315	585	0	0	431	0	0	783	0	3574
900	431	2787	900	0	0	129	302	0	1344	1442	0	1516
900	431	4790	900	0	0	410	21	0	2490	1722	0	89
900	3166	783	900	0	0	1698	1467	0	507	276	0	785
900	3166	2787	828	0	72	1890	1276	0	1082	468	0	0
900	3166	4790	828	0	72	1890	1276	0	1082	468	0	0
900	5900	783	828	0	72	2388	1741	0	584	3	0	0
900	5900	2787	828	0	72	2425	1705	0	548	39	0	0
900	5900	4790	828	0	72	2425	1705	0	548	39	0	0
1286	431	783	701	585	0	0	431	0	0	783	0	3188
1286	431	2787	1286	0	0	130	301	0	1344	1443	0	1130
1286	431	4790	1214	0	72	291	140	0	2296	1604	0	0
1286	3166	783	1286	0	0	1698	1468	0	507	276	0	399
1286	3166	2787	1182	0	72	1801	1364	0	817	380	0	0
1286	3166	4790	1182	0	72	1801	1364	0	817	380	0	0
1286	5900	783	1168	0	72	2578	1542	0	54	202	0	0
1286	5900	2787	1168	0	72	2582	1537	0	50	206	0	0
1286	5900	4790	1168	0	72	2582	1537	0	50	206	0	0
1672	431	783	1087	585	0	0	431	0	0	783	0	2802
1672	431	2787	1672	0	0	131	300	0	1343	1444	0	744
1672	431	4790	1525	0	72	123	308	0	2153	1435	0	0
1672	3166	783	1595	0	72	1698	1467	0	507	276	0	0
1672	3166	2787	1182	0	72	1801	1364	0	817	380	0	0
1672	3166	4790	1182	0	72	1801	1364	0	817	380	0	0
1672	5900	783	1168	0	72	2573	1547	0	59	197	0	0
1672	5900	2787	1168	0	72	2631	1489	0	1	255	0	0
1672	5900	4790	1168	0	72	2631	1489	0	1	255	0	0

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