Strategies for 2nd generation biofuels in EU – Co-firing to stimulate feedstock supply development and process integration to improve energy efficiency and economic competitiveness

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Abstract
The present biofuel policies in the European Union primarily stimulate 1st generation biofuels that are produced based on conventional food crops. They may be a distraction from lignocellulose based 2nd generation biofuels – and also from biomass use for heat and electricity – by keeping farmers’ attention and significant investments focusing on first generation biofuels and the cultivation of conventional food crops as feedstocks. This article presents two strategies that can contribute to the development of 2nd generation biofuels based on lignocellulosic feedstocks. The integration of gasification-based biofuel plants in district heating systems is one option for increasing the energy efficiency and improving the economic competitiveness of such biofuels. Another option, biomass co-firing with coal, generates high-efficiency biomass electricity and reduces CO2 emissions by replacing coal. It also offers a near-term market for lignocellulosic biomass, which can stimulate development of supply systems for biomass also suitable as feedstock for 2nd generation biofuels. Regardless of the long-term priorities of biomass use for energy, the stimulation of lignocellulosic biomass production by development of near term and cost-effective markets is judged to be a no-regrets strategy for Europe. Strategies that induce a relevant development and exploit existing energy infrastructures in order to reduce risk and reach lower costs, are proposed an attractive complement the present and prospective biofuel policies.

1. Introduction

1.1. The present situation for biofuels in the European Union

The production and use of biofuels for transport are growing rapidly in the European Union (EU). So-called 1st generation biofuels, such as cereal ethanol and rapeseed biodiesel completely dominate domestic production, which is supplemented by imports of primarily biodiesel from palm and soy oil and ethanol from sugarcane. The conversion technologies for 2nd generation lignocellulose based biofuels are not yet commercially available [1]. Both the lignocellulosic ethanol option and the biomass gasification option, that can provide...
a wide range of liquid and gaseous fuels, are presently in the pilot/demo stage. A few near-commercial projects are underway and may be operational within a few years, but the more extensive deployment of full scale plants will likely become a post-2015 response to climate and energy policies – given that these maintain the focus on biofuels as the path for transport sector transformation to become more climate friendly and less vulnerable to supply.

Besides the challenges of developing the conversion technologies, the supply infrastructures for 2nd generation biofuel feedstocks have not yet been widely established. In member states (MS) having large forestry sectors there is a wood supply infrastructure in place. In a few MS such as Sweden and Finland the use of forest wood for energy has grown to a substantial activity and this has influenced the wood supply infrastructure. But in most MS, the wood supply infrastructure has still to develop in response to changing demand patterns, as bioenergy becomes an increasingly important end use. This development does not only concern technology and economics of logistical systems, but also institutional development: regulations need to reflect the new situation and ensure that the increased forest biomass output respects sustainability restrictions (which in many instances need to be understood first). One example is the increased utilization of residues in forests, including stumps, that require regulation and compensating measures to maintain nutrient balances. Also, the increased forest wood demand in general can be expected to stimulate measures to intensify forestry, e.g., by forest fertilization. This intensification needs to be managed in a responsible way.

In the agricultural sector, the lignocellulosic output so far mainly consists of fibre crops for non-energy purposes and harvest residues in conventional food/feed crop production, straw being the most common residue. The harvest residues are mainly collected for non-energy purposes such as animal feeding and bedding but in a few MS also for energy purposes (heat and power). Willow has been grown commercially for heat and power in Sweden since the beginning of the 1990s, and the plantations now amount to some 14,000 ha, or about 0.5% of the Swedish arable land [2]. Thus, despite this experience of soon 20 years of cultivation, forest supplies dominate in biomass-based heat and power and willow production is still an emerging agricultural activity with a small land claim. A very limited cultivation of lignocellulosic crops for energy exists in a few other MS.

1.2. Feedstock supply prospects in EU

Fig. 1 indicates the feedstock supply prospects for the case of forest biomass, showing the current wood removals and also the prospects for increased removals from forests. Current removals on forests available for wood supply (x-axis in Fig. 1) consist of (i) the part of fellings that is removed from the forest and (ii) the removals of trees killed or damaged by natural causes such as windblow, insects and diseases (natural losses). It excludes silvicultural and pre-commercial thinnings and cleanings left in the forest, and natural losses that are not recovered. The volumes of removals are indicative of the magnitude of the current biomass flows in the forest sector that might be available for energy purposes, since the by-flows (felling residues, silvicultural and pre-commercial thinnings, and process by-flows in the forest industry such as sawdust and black liquor) are of the same magnitude as the biomass flow in the form of products. The products are also to a significant part used for energy after having served its primary function. The current removals are given in comparison to the domestic gross energy consumption, which means that the further to the right a country is in Fig. 1, the larger is the current removals in relation to the country’s gross energy consumption. Sweden and Finland have the largest annual removals in EU, corresponding to roughly 600 and 500 PJ, respectively, and as can be seen in Fig. 1 the extraction

![Fig. 1 – Comparison between current gross energy consumption and: (x-axis) wood removals on forests available for wood supply; and (y-axis) the balance between net annual increment and current removals in the MS. The forest extraction and balance are converted to energy units based on assumed energy content of 10 GJ m$^{-3}$ of wood and then divided by each country’s gross energy consumption. Data sources: Eurostat statistical database and [3].](image-url)
is also substantial relative to the domestic energy use. The three Baltic States and a few other MS also have a significant forest extraction relative to their own energy use. Forest wood extraction is also large in France and Germany, but compared to the energy use in these countries it is only a few percent. Forest extraction in Poland is about half the level in Finland and in Austria it is roughly one-third of the Finnish level.

The net annual increment (NAI) minus current removals (y-axis) is a rough indication of how much the removal can increase in a given country. NAI refers to the average annual volume of increment of all trees, with no minimum diameter, minus natural losses. It is thus equivalent to natural forest growth in a year (minus the natural losses). Countries close to the dotted diagonal have a non-used NAI that is roughly equal to the current removals or, in other words, the total NAI is twice as large as the current removals. The further up a country is in the diagram, the larger is the non-used NAI compared to the country’s gross energy consumption.

As can be seen, several countries could increase their removals from forests substantially, although in many countries this possibility to increase the removals is still rather small (less than 10%) in relation to the country’s gross energy consumption. For the entire EU, the current wood removal corresponds in energy terms to about 5% of the gross energy consumption and even if the removal became as large as the net annual increment, it would still be relatively modest compared to the climate neutral energy supply that will be required for the EU to reach climate and energy policy targets.

The supply potential of energy crops and agricultural residues is reported elsewhere in this special issue [4,5] and is therefore not explicitly treated here. In summary, it can be concluded that a substantial potential for lignocellulosic crops on agricultural areas in EU was found, including lands not suitable for the cultivation of conventional food/feed crops (primarily pastures and grasslands) due to that this would lead to significant soil carbon (C) losses and also risk causing other negative environmental impacts. REFUEL analyses [6,7] also confirm the finding reported in other studies (see, e.g., [9]) that the production cost for lignocellulosic crops can go down substantially over time due to learning and benefits of large-scale establishment. The agricultural residue potential was found to be of similar magnitude as the assessed energy crop potentials in EU15, but for Europe as a whole (especially if including Ukraine) the assessed potential of energy crops in 2030 is 3–4 times larger [4,5]. Thus, lignocellulosic crops could become the major feedstock source in a prospective situation where 2nd generation biofuels (as well as biomass-based heat and power) are playing a more prominent role in the EU’s energy mix.

1.3. Do the policies put in place effectively pave the way for 2nd generation biofuels?

The importance of lignocellulosic crops has also been recognized by the European Commission (EC), which in its communication An EU strategy for Biofuels includes as one of three main aims “...to prepare for the large-scale use of biofuels by improving their cost-competitiveness through the optimized cultivation of dedicated feedstocks, research into “second generation” biofuels, and support for market penetration by scaling up demonstration projects and removing non-technical barriers” [9].

However, it can be questioned whether policies put in place so far effectively pave the way for 2nd generation biofuels and lignocellulosic bioenergy options in general. The introduced biofuels’ targets do not seem to induce the robust development of conversion technologies for these biofuels. In fact there are indications that the targets are even counter-productive regarding the development for lignocellulosic crops: farmers are less inclined to try lignocellulosic crops as long as they see good prospects for staying with the conventional crops, and since many farmers have invested with this expectation in mind they may even see the possibility of a shift to 2nd generation biofuels as a threat rather than an opportunity. Since not only 1st generation feedstock cultivation but also the entire production chain would become unprofitable in the instance of a shift to 2nd generation biofuels, one can expect that stakeholders that have invested in the 1st generation biofuel production plants (which includes farmer-owned companies) will lobby for conserving the position of 1st generation biofuels on the market.

Policymakers can promote the development of 2nd generation conversion technologies by, e.g., introducing specific targets for 2nd generation biofuels and R&D support. Such initiatives could be complemented by initiatives that stimulate the development of the lignocellulosic feedstock supply systems and especially of lignocellulosic crops. Important initiatives include (i) research on cultivation practices of perennial crops; (ii) adaptation of the EU common agricultural policy and spatial policies in order to accommodate them; and (iii) cross-sector policy harmonisation. Additionally important is the creation of near-term markets for the lignocellulosic feedstocks and exploitation of expansion pathways for 2nd generation biofuels that are lower in cost and entail low risk.

Looking wider, not only biofuels for transport but also bioenergy in general is hampered by barriers both on the supply side – with the significant potentials mostly unexploited so far – and on the conversion side – where a biomass-to-energy conversion infrastructure is lacking in most countries. The introduction of such infrastructure will be costly both in terms of direct costs (e.g. investments in new power plants) and in indirect costs (e.g. investments in district heating systems). In addition, the large need for new investments in heat/power generation in several MS may result in a lock-in situation dominated by power generation based on coal and natural gas, with technologies not appropriate for biomass use.

Thus, the identification of near-term bioenergy markets and cost-effective implementation paths for lignocellulosic biomass is well motivated regardless of which biomass uses that will dominate on the longer term.

This paper presents results from analyses of two strategies for the promotion of cost-effective implementation paths for 2nd generation biofuels based on lignocellulosic feedstocks. Considering that the EC in its Biomass Action Plan emphasized that biomass should be promoted in all three sectors – i.e. transport, heat and power production – the strategies furthermore aim at supporting development also in the fields of heat and power. They have in common that they exploit existing energy infrastructures in order to reach lower costs.
2. Strategies for 2nd generation biofuels

2.1. Integration of biofuel production plants with district heating systems

This first strategy – only briefly described in this paper – focuses on biofuel production processes that are based on biomass gasification with subsequent synthesis to biofuels such as FT diesel, DME, methanol and methane (see e.g., [10–13]). These plants generate excess heat and in order to enhance energy efficiency (as well as improve the economic viability) the process can be designed so that part of the heat losses can be usefully applied in district heating (DH) systems. The integration of these types of biofuel plants with DH systems would improve the cost-competitiveness of these biofuels, particularly when replacing decommissioned heat generation capacity in existing DH systems or when investments are made to extend the DH systems. For some biofuel plant configurations also electricity can be produced, further improving the cost-competitiveness.

The existing DH systems in EU25 (Fig. 2) deliver about 10% of the total annual heat demand and the contribution varies among the MS reaching as most about 30% in the Baltic States and Denmark (estimation for 2003 based on [14,15]). Ireland and Greece have relatively small DH systems, and Malta, Cyprus and Spain completely lack DH systems. Some MS primarily use heat from combined heat and power (CHP) plants and waste heat from other industrial processes as dominating input for their DH systems, while other MS to a large extent also produce heat directly for the DH systems in heat only boilers (HOB). In 2003, about 80% of the heat used in the more than 5000 DH systems in EU25 was produced in fossil fuel fired CHP plants (about 60%) or HOB plants (about 30%) [15].

Since most of the present DH heat deliveries in EU are based on fossil fuels, this strategy represents an opportunity to simultaneously increase the biomass use and reduce CO₂ emissions both in the heat, electricity, and transportation sectors. It could contribute to meeting the EU-targets for increased energy efficiency, for renewable energy, as well as for biofuels for transportation. To illustrate the size of the current DH systems in EU25 in relation to the EU biofuels for transportation targets for 2020: if 10% of the projected transport energy demand in EU by 2020 was to be met with biofuels from DH integrated production delivering 0.2 energy units of DH heat per energy unit of biofuel produced, these biofuel plants would cover roughly 15% of the total heat demand in the current DH systems in EU25.

The analyses show that the possibility for implementation of DH integrated biofuel production is highly dependent on the competitiveness against other heat supply options and in particularly CHP, which is dominating the DH heat supply in most MS. It is also dependent on whether an economic feasibility requires that the DH integrated biofuel plant becomes a base load heat provider for the DH system. If this is the case and at the same time DH integrated biofuel production is not competitive against CHP in situations of renewal/expansion of the heat generation capacity in the DH systems, the contribution of this biofuel option will likely be rather small. Estonia and France are the only MS that to a large extent use fossil HOB for base load DH heat supply (about 50% and 70%, respectively). On the other hand, if the biofuel plants successfully compete against CHP, a large heat sink would be available. Illustrating the size once more: if the heat demand otherwise covered by CHP was instead covered by DH
integrated biofuel plants providing base load heat (at least 4000 operating hours per year), about 9 EJ of biofuels would be produced. This corresponds to roughly 60% of final energy consumption in the transport sector year 2005.

There are many factors that influence the implementation possibilities of DH integrated biofuel production that require more detailed analyses on country/DH-system level. Examples of such factors are local biomass availability, total size and internal heat transfer capacity of individual DH systems, and policies influencing the price of fossil/renewable heat, electricity and transport fuels. The energy system impacts of implementing DH integrated biofuel production (e.g., energy efficiency and CO₂ emissions) also need further analysis. A dramatic expansion of DH integrated biofuel production at the expense of reduced CHP production would lead to reduced electricity generation. Depending on how this lost generation is compensated for, the climate benefit of expanding DH integrated biofuel production may look very different on a total energy- and transport system level. For example, if coal based power expands, much of the climate benefits from replacing diesel/gasoline with the produced biofuels will be lost.

A more comprehensive presentation of the possibilities for DH integrated biofuel production in EU will be available in a forthcoming paper. In the next section, the second strategy explored in REFUEL – biomass co-firing with coal – is described. Hansson et al. [16] give a more detailed account of the prospects for co-firing in EU27. For a further in-depth account of technology and other aspects of biomass co-firing, Leckner [17] provides a readable summary of co-firing technology, and IEA Bioenergy task 32 (http://www.ieabcc.nl/) provides both comprehensive information and an extensive network within the fields of biomass combustion and co-firing.

2.2. Biomass co-firing with coal

Co-firing is the simultaneous combustion of two or more fuels in the same plant in order to produce one or more energy carriers. Co-firing biomass with coal in existing boilers costs about 2–5 times less to implement than other bio-electricity generating options and is also in the lower cost range compared to other renewable energy based electricity (RES-E) options [18]. Biomass co-firing with coal is more efficient than other available bio-electricity options since the impact on conversion efficiency from low levels of biomass co-firing seems to be modest (e.g., [19,20]). The typical conversion efficiency for a dedicated biomass-fired power plant is 25% [21]. The average conversion efficiency for conventional coal-fired power plants (so-called subcritical pulverized plants) is around 36% in OECD countries [22], with new state of the art plants reaching at least 43% [23].

Biomass co-firing holds the advantage of making use of the infrastructure associated with the coal power plants and represents a bioenergy expansion that is not constrained by the rate at which new bioenergy conversion facilities can be put in place. Also, uncertain biomass supplies do not jeopardize the fuel supply for power plant owners, who can manage a temporary loss on the biomass supply side (or short-term biomass price volatility) by increasing the share of coal in the fuel mix. This fuel flexibility also works the other way around: plant owners can increase the share of biomass in the fuel mix (up to technically defined limits) in response to low biomass prices and/or high RES-E prices.

Thus, biomass co-firing with coal has been proposed as a near term, low-cost way to use biomass (e.g. lignocellulosic feedstocks) for reducing CO₂ emissions (e.g. [24,25]). As such, it offers an opportunity to stimulate the development of lignocellulosic supply systems, while offering several additional benefits: it provides low-cost RES-E and substantial CO₂ reductions as the biomass replaces the most carbon intensive electricity generation.

2.2.1. The potential of biomass co-firing with coal in EU

Globally, roughly 5 EJ of biomass/waste could in theory be burned in coal power plants every year, assuming that biomass could be co-fired in all coal-fired power plants at a 10% fuel share, on energy basis [20]. Experience shows that such biomass levels can be co-fired without any major problems of alkali related high temperature corrosion, slagging and fouling (see, e.g., [20,26,27]). The large number of coal-fired power plants also makes biomass co-firing an option in many MS. Europe has roughly two-thirds of about 150 coal-fired power plants presently co-firing biomass, either as pilot tests or in commercial use [28]. A wide variety of biomass materials, including herbaceous and woody materials, wet and dry agricultural residues and energy crops are used [21].

The analysis of the potential for biomass co-firing in existing coal-fired power plants in EU has used the Chalmers Power Plant Database (CPPD), which contains information about all plants in EU (plus Norway and Switzerland) with a capacity generally exceeding 10 MWe, covering 97% of the total net capacity of plants in operation in the region as given by Eurostat [29] (see [16] for a more comprehensive description of methodology and results). The geographic locations of the power plants included in the CPPD are presented in Fig. 3 and selected country-level data are presented in Table 1. Besides the location, the CPPD includes the name, position, fuel type, net power capacity, and age of power plants. It also contains information about plants under construction or planned [30].

The CPPD is one of several databases that are developed and continuously updated in order to support studies requiring a detailed description of the current European stationary energy system – and considering also the related infrastructure with their limitations and possibilities. The CPPD in itself also contains information about cross-border transmission capacity and thermal production and is complemented by the CO₂ Storage Database and the Fuel Database on the supply side. The Demand Side Database is under development and relevant policies in the different MS are collected into a Policy Database [31].

The near-term technical biomass co-firing potential is here defined as the maximum amount of bio-electricity that can be produced from biomass co-firing in the existing coal-fired power plant infrastructure. A brief account of the approach to estimating this potential is given below and the reader is referred to Hansson et al. [16] for further information.

The near-term technical biomass co-firing was calculated based on:
the available boiler capacity for co-firing in the different MS, which was taken from the CPPD. The capacity was quantified for three separate boiler types: fluidised bed boilers, pulverized coal-fired boilers, and grate-fired boilers; the estimated load factor, which was estimated on a nation by nation basis and for plants using lignite and hard coal separately. This was done based on the 2004 annual national power generation by fuel [32] and the national total capacity for the two kinds of coal, obtained from the CPPD; the assumed maximum biomass share in the fuel mix for the different boiler types included in the CPPD, which was set to 15% for fluidised bed boilers and 10% for pulverized coal-fired and grate-fired boilers (energy basis).

The corresponding potential biomass demand for co-firing was then readily obtained based on assuming that the inclusion of biomass in the fuel mix does not reduce the conversion efficiencies in the power plants, which were set to 30% for plants 31–40 years old; 35% for plants 21–30 years old; 37% for plants 11–20 years old; 40% for plants 0–10 years old; and 45% for plants under construction and planning. Note that the term “potential biomass demand for co-firing” should here not be interpreted as projected demand for biomass for co-firing in any future year: it is an indication of the prospective size of this specific biomass use in the different MS and will below be discussed in relation to the possibility that biomass co-firing could function as a stepping stone for 2nd generation biofuels by stimulating development and cost reduction on the feedstock supply side.

The role of biomass co-firing for future electricity in EU is further discussed in [16]. It can just be noted here that biomass co-firing could become an important option in relation to future RES-E targets in several MS. If considering all coal-fired power plants less than 40 years old, the technical biomass co-firing potential is roughly as large as the total biomass-based electricity production in EU27 in 2005 [16].

2.2.2. Biomass co-firing with coal as a stepping stone for 2nd generation biofuels
Could a prospective biomass demand for co-firing bridge to 2nd generation biofuels by stimulating a substantial development of lignocellulosic supply systems, compared to what would be required for supporting a 2nd generation biofuels’ industry? Looking at absolute sizes initially, the potential biomass demand for co-firing is about 500 PJ in EU27 for a case where only power plants below an age of 30 years are considered available for conversion to co-firing. If power plants up to an age of 40 years are considered available, the potential biomass demand for co-firing would increase to more than 900 PJ and it would increase notably in several MS – in particular the UK. Clearly, these biomass demand numbers are calculated based on the set load factors, conversion efficiencies and biomass shares in the fuel mix. They should therefore be considered indicative since these parameters can vary and depend on technology development as well as market prices for biomass, coal, green electricity, CO2 emissions, etc.

The potential biomass demand for co-firing varies substantially among the MS, which is an obvious outcome of
the varying importance of coal based power in the different MS. However, for many MS the potential biomass demand for co-firing is substantial in relation to the amount of biomass needed to meet a 10% target for biofuels in 2010. In Fig. 4, the potential biomass demand for co-firing is compared to the amount of biomass needed to meet a 10% target in 2010 in EU27 and in the top-12 EU MS (assuming conversion efficiency from biomass to biofuels at 50 %). The comparison is made for the two cases where power plants more than 30 and 40 years old (Case 1 and Case 2, respectively) are assumed to be available for co-firing. On an EU level the estimated potential biomass demand for co-firing corresponds to about 15% (Case 1) and 25% (Case 2) of the biomass needed to reach the EU biofuels for transportation target at 10%.

Thus, from the perspective of absolute size biomass co-firing with coal clearly qualifies as a potentially important near-term biomass demand source in many MS: if biomass co-firing expands strongly in response to policy targets and other stimulating mechanisms biomass output for energy would have to increase substantially in many MS.

At the same time, the bioenergy supply potentials estimated in the REFUEL project [3,4] are much larger than the potential biomass demand for co-firing, implying that there is low risk that biomass demand for co-firing would deplete biomass markets, unless strong (institutional or other) supply side barriers prevent a supply side response to increasing biomass demand. In fact, the estimates indicate that the potential biomass demand for co-firing could be met using only residues in agriculture and forestry, implying that stimulation of lignocellulosic crop production might require specific policies linking co-firing with such biomass sources (e.g., by requiring that a certain share of the co-fired biomass is from lignocellulosic crops). This is also true when considering the possibility of biomass imports. Availability of cheap biomass from third countries might prevent that biomass demand for co-firing stimulates the development of a domestic biomass supply infrastructure. For instance, more than half of the biomass used for co-firing with coal in the UK in 2005 consisted of vegetable oil residual products (e.g., palm, olive and sunflower) [34].

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### Table 1 – Estimated average national load factors for coal-fired power plants in the MS having such plants. Also given is the capacity per boiler type and the number of plants (each boiler is treated separately). Based on CPPD and Eurostat [32]. See Hansson et al. [16] for more detailed information.

<table>
<thead>
<tr>
<th>MS</th>
<th>Load factor (hours per year)a</th>
<th>Hard coal</th>
<th>Lignite</th>
<th>Fluidised bed boilers</th>
<th>Pulverized coal boilers and grate-fired boilers</th>
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<tr>
<td>Austria (A)</td>
<td>4707</td>
<td>2529</td>
<td></td>
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<td>3416</td>
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<td>1780</td>
<td>4545</td>
<td></td>
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<td>4693</td>
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<td>9.54 (79)</td>
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<tr>
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</tbody>
</table>

a The load factors are in many cases surprisingly low but depend on the large amount of relatively old boilers, especially in the Eastern Europe, requiring more maintenance. Note also that for some countries (Austria, Finland, Ireland, and Spain) the load factors for hard coal are higher than for lignite contrary to what is expected. The reason can be the use of different sources (Eurostat, 2006 for the national electricity production and CPPD for the total national capacity for the fuels), which might not include the exact corresponding information. See also [16].

b The same load factor is used for lignite and hard coal in both the Czech Republic and Romania, due to differences in the reporting of coal use in the sources.
The proposed stepping-stone function of biomass co-firing with coal presumes that it represents a near-term market for lignocellulosic biomass that gradually decreases over time, making place for 2nd generation biofuel technologies as the major subsequent use of the lignocellulosic biomass – benefiting from the already established biomass supply infrastructure. Obviously, the analyses presented here that primarily focused on the existing coal-fired power plant infrastructure meet the criterion of being a near-term option that will not compete for biomass on the longer term, since the power plants will eventually be shut down due to high age (see Fig. 5).

However, to the extent that new coal-fired power plants are built (possibly prepared for co-firing from the start) this option might prevail as a competing biomass use also on the longer term. New technology development may make biomass co-firing with coal competitive also in a future climate regime with high CO₂ prices (arising e.g. from the EU-emission trading scheme). For instance, if carbon capture and storage becomes widely available, biomass co-firing with coal may become a long-term option for low-CO₂ power (possibly even providing power associated with negative CO₂ emissions). This can also be the case if biomass preparation technologies allow for substantially higher biomass shares in the fuel mix. For instance, a combination of torrefaction with washing out the mineral salts might produce solid biofuels that can be co-fired in high percentages with coal without causing the problems associated with burning biofuels with high alkali content [35].

A geo-spatial view of biomass co-firing opportunities in relation to biomass supply potentials and preferred locations for 2nd generation biofuel plants would improve the understanding of how co-firing could influence short and medium term development. Ongoing analyses include geo-spatial considerations but no results are yet available for reporting.

3. Concluding discussion

In the context of biofuel development in EU, this article has proposed strategies for paving the way for 2nd generation biofuels. Two specific examples have been described that have in common that they exploit existing energy infrastructures in order to reduce risk and reach low costs. The assessment of the prospects for DH integrated biofuel production showed that the DH systems in EU represent a large heat sink in relation to the amount of excess heat that could be delivered from biofuel plants that are based on biomass gasification with subsequent synthesis to biofuels, if such plants provided biofuels sufficient for meeting the EU 2020 target for biofuels for transport. However, many factors influence the implementation potential for this biofuel option and require further analysis. Not the least the energy system impacts of implementing DH integrated biofuel production need to be analysed more.
From the perspective of biomass co-firing paving the way for 2nd generation biofuels, a steady growing biomass demand for co-firing may be considered a lock-in risk. But if biomass co-firing grows steadily in the context of a carbon cap complying with an ambitious climate target (and the transport sector contributes substantially), co-firing may just represent a cost-effective use of biomass resources. The transport systems may then have evolved to a state where climate compatible technologies other than those based on biofuels are dominant. The essence of the strategy is that it starts up biomass supply chains, and leaves their long-term application open to future investment decisions, either preferring new advanced multi-fuel power plants, 2nd generation biofuel plants, or may be new types of plants that co-generate fuels, power and heat from biomass, coal and gas.

As long as the attractiveness of biomass co-firing is dependent on a governmental strategy package involving specific policy instruments promoting this option, appropriate modifications can be incorporated into this strategy to address concerns about large co-firing demand preventing other, possibly more desirable bioenergy developments. Similarly, policies can be tailored so as to link specific biomass supplies to the co-firing market: there can for instance be a differentiation between lignocellulosic crops and residues in the agriculture and forest sectors, or between domestic and imported biomass.

As often, policymakers need to choose between (i) defining broad goals and let markets shape the (most cost-effective) development, and (ii) promoting a specific development that is dependent on a governmental strategy package involving specific policy instruments promoting this option, appropriate modifications can be incorporated into this strategy to address concerns about large co-firing demand preventing other, possibly more desirable bioenergy developments. Similarly, policies can be tailored so as to link specific biomass supplies to the co-firing market: there can for instance be a differentiation between lignocellulosic crops and residues in the agriculture and forest sectors, or between domestic and imported biomass.

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Regardless of the long-term priorities of biomass use for energy, the stimulation of lignocellulosic biomass production by development of near term and cost-effective markets seems to be a no-regret strategy for Europe.

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REFERENCES


