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CASE STUDY BIOBASED CLUSTER AT THE PORT OF ROTTERDAM

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EXECUTIVE SUMMARY

Background

The Biomass Policies project [1], supported by the Intelligent Energy Europe (IEE) programme, aims to improve the policy framework for the mobilisation of indigenous bioenergy value chains in contributing to the 2020 renewable energy targets and beyond. The project pays particular attention to competition in different sectors for the available biomass, resource efficiency and sustainability.

Resource efficiency has been defined as "producing more with less while avoiding environmental impacts [2]". Different than the other renewable energy sources biomass, when utilized unsustainably, can cause significant socio-economic and environmental implications. It is, therefore, particularly important to consider resource efficiency principles when developing integrated polices for bioenergy.

Biorefinery/cascading systems can play a key role in this process through refining the high quality fractions of biomass for high quality products, and the low quality fractions of biomass for energy. Biorefineries are defined as promising integrated approach for the co-production of both value-added products (bio-materials, bio-chemicals, bio-plastics, food, feed) and bioenergy (biofuels, biogas, heat and/or electricity) [3].

Objectives

This case study focuses on a specific integrated biorefinery concept, namely the integration of bioethanol/polylactic acid (PLA) production and the co-firing of biomass in a coal-fired power plant at the Port of Rotterdam, with the ambition to contribute to the discussions around resource efficient use of biomass and to the development of integrated policies that promote resource efficient use of biomass in Europe. The specific objectives of the case study are to:

- Discuss the resource efficiency concept and some of its proposed indicators in a concrete case and provide recommendations on this;
- Analyse the possible role of existing bioenergy policy support instruments on the profitability of an integrated biorefinery concept;
- Discuss the possible future role of biomass co-firing in an integrated biorefinery concept.

Methodology

The methodology used in this case study is based on a biorefinery model, developed by ECN, within the FP7 project Bioref-Integ [4]. Based on the mass, energy and economic data of a process, the production costs of the main product for both a reference case, as well as for an integrated biorefinery scheme are calculated, with the objective to evaluate to what extent the integrated biorefinery scheme could enhance the economic competitiveness of the main product, compared to the reference case.

Considered cases

The following three cases have been considered:

- Co-firing of wood pellets (Reference I);
- Stand-alone PLA plant (Reference II);
- Biobased PLA-co-firing cluster.

In case of the co-firing plant, electricity is the main product. All the variable and fixed costs have been divided by the total annual electricity production, in order to calculate the production cost of electricity from co-firing of wood pellets in €/MWh_{el}. In case of the stand-alone plant, PLA is the main product. All the variable and fixed costs have been divided by the total annual PLA production, in order to calculate the production cost of PLA from wood chips in €/t_{PLA}. The considered biobased cluster integrates the two reference cases. PLA will be the main product, and its production cost has been calculated in the same way as mentioned for the stand-alone plant. The calculated electricity production cost for the co-firing reference case has been compared with the SDE+ subsidy parameters [5], while the calculated production cost for the produced PLA has been compared with the market value for PLA.

Co-firing of wood pellets (Ref. I)

Under the system boundaries taken in this study, the production cost of electricity is 88 €/MWh_{el}, while the 2015 market price has been estimated at 43 €/MWh_{el}. The difference – i.e. 45 €/MWh_{el} – is the subsidy required for a zero Net Present Value (NPV). The difference between the SDE+ subsidy of 72 €/MWh_{el} and 45 €/MWh_{el} should cover the loan interest, the return on equity, and the inflation, as assumed within SDE+ [5]. The required biomass contributes to 88% of the production cost. In order to come to a zero NPV without any subsidy, the wood pellets cost should decrease to about 40% of the current cost (at constant values for other assumptions), i.e. 67 €/tonne compared to 160 €/tonne, which is unlikely to happen.

Stand-alone PLA plant (Ref. II)

The production cost of PLA, excluding the SDE+ subsidy for CHP, while including the double counting measure for the co-produced bioethanol, is about 1000 €/t PLA. For comparison the market values of PLA (low and high) are 1700 resp. 3000 €/t PLA. Based on the assumptions made, this reference case is therefore economically feasible, even without an SDE+ subsidy for the CHP installation. This reference case is an example of a biorefinery and cascading principle, in which wood chips are converted to a bio-material (PLA), a biofuel (bioethanol), heat and electricity. However, while lactic acid production from fermentation of sugars from sugar crops or starch crops are at full commercial application, lactic acid production based on lignocellulosic biomass is still at the Technology Readiness Levels (TRLs) of 3 to 5 (applied research/large-scale prototype). In other words, it still takes time before this technology would become full commercial.

Biobased PLA-co-firing cluster

In this case the above-described references are integrated into a biobased PLA-co-firing cluster. In comparison to reference I (co-firing plant), more than 70% of the wood pellets are replaced by the lignin fraction of the wood chips. Therefore, only less than 30% of the wood pellets are still required to produce the same amount of electricity as in the reference I. In comparison to reference II (stand-alone PLA plant), the existing co-firing plant will replace the CHP installation. In this way, a large investment of about 40% of the total investment for the reference II will be avoided. The production cost of PLA, excluding the SDE+ subsidy for CHP, while including the double counting measure for the produced bioethanol, is about 800 €/t PLA. For comparison the market values of PLA (low and high) are 1700 resp. 3000 €/t PLA. Based on the assumptions made, this integrated case is therefore economically feasible, even without an SDE+ subsidy for co-firing. This is a major advantage of this case compared to reference I, in which co-firing of biomass seems to remain dependent on subsidy, even in the future. Compared to reference II, the production cost of PLA is 20% lower (800 versus 1000 €/t PLA). This is mainly due to the difference in investment costs of the CHP installation and the co-firing plant, followed by a higher value for the produced electricity via co-firing, compared to the value of combined heat and electricity production via CHP. On the other hand, the cost of required wood pellets is an additional expense compared to reference II.

A question that arises regarding this biobased cluster is the future of SDE+ subsidy for biomass co-firing in the Netherlands. Although this option is important for achieving the Dutch RE targets in 2020 and 2023, the continuation of the SDE+ for co-firing after 2023 is uncertain. On the other hand, lactic acid production based on lignocellulosic biomass is expected to become full commercial after 2020-2023. Such an integrated biobased cluster could then offer the opportunity to deliver (partly) much cheaper biomass than wood pellets for co-firing. In absence of a co-firing plant the available lignin, depending on the location, availability of a heat source, technological development, could either be combusted in a biomass CHP plant, be sold as a fuel, or it can be used in lignin chemistry.

Sensitivity analysis

In order to assess the effect of relevant input parameters on the production cost of the main products, a number of sensitivity analyses have been performed. The following input parameters have been considered:

- Cost of biomass;
- Investment cost of CHP;
- Market price of 2nd generation bioethanol;
- Conversion efficiency of C6 sugars to PLA;
- Conversion efficiency of C5 sugars to ethanol.

None of the performed variations have led to a higher PLA production cost than its market value. This, however, might be the case by a combination of parameter variations, but in general, the positive outcome for the integrated system seems quite robust.

Cost of biomass

Cost of biomass, i.e. wood pellets and/or wood chips has been varied from 50% to 150% of the reference value for three considered cases. As a result:

- The production cost of electricity for Ref. I will change to 56% resp. 127% of the cost in the reference case. Even at the lowest wood pellets cost, the production cost is higher than the market price for electricity.
- The production cost of PLA will be 73% to 127% of the cost for the Ref. II, and 59% to 141% of the cost for the biobased cluster.

Investment cost of CHP

Varying the investment cost of the CHP installation for the Ref. II case from 50% to 150% of the reference value leads to 15% decrease or increase of the production cost for PLA.

Market price of 2nd generation bioethanol

It is uncertain whether the double counting regulation would continue to exist after 2020. We have, therefore, compared the reference situation including double counting for the stand-alone PLA plant and the integrated case, with situations in which the market price for 2nd generation bioethanol equals that of 1st generation bioethanol, or even equals the market price of gasoline. Such variations lead to increase of the production cost for PLA up to:

- 17% resp. 34% for the stand-alone PLA plant;
- 21% resp. 42% for the integrated case.

Conversion efficiency of C6 sugars to PLA

For each 5% variation in the conversion efficiency of C6 sugars to PLA, the production cost of PLA will change for 5% in case of the Ref. II, and 8% for the integrated cluster.

Conversion efficiency of C5 sugars to ethanol

Conversion efficiency of C5 sugars to ethanol has indirectly been varied for the stand-alone PLA plant and the integrated case, by decreasing the volume of ethanol produced by 10%, resp. 20%. For each 10% decrease in the volume of produced ethanol the production cost of PLA will decrease for about 6% for the stand-alone PLA plant and 8% for the integrated case.

Resource efficiency

The following three indicators have been used to evaluate the resource efficiency of the considered value chains:

- Energy-based resource efficiency: net energy output per unit biomass;
- Economy-based resource efficiency: net value added per unit biomass;
- Environmental-based resource efficiency: net CO_2 avoided per unit biomass.

Energy-based resource efficiency

Figure 1 presents the energy-based resource efficiency for different cases. The co-firing plant (ref. I) has the highest energy-based resource efficiency, followed by the stand-alone PLA plant (ref. II) and the biobased cluster. The joint ref. I and ref. II has higher energy-based resource efficiency than the biobased cluster. The main reason for such an order in the resource efficiency of the cases is, that this indicator does not take the quality of the final energy and produced materials into account. There is no difference between 1 GJ of heat (no matter whether it is high quality steam or hot water) and 1 GJ of electricity, or bioethanol, or PLA. Based on this indicator, a final product like heat, which is at the bottom of the value pyramid, will have the highest energy-based resource efficiency. Of course the production of bio-materials with much more process steps, compared to heat and/or power production, will lead to a lower overall energy-based resource efficiency. This indicator, therefore, is not a suitable measure for evaluating the value chains based on biorefinery/cascading principle.

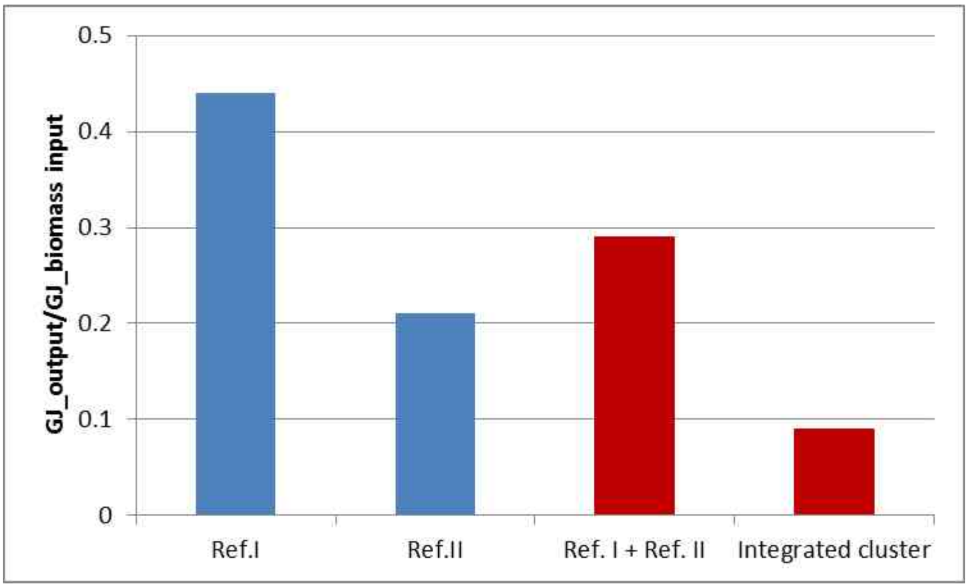

Figure 1: Energy-based resource efficiency for different cases

Economy-based resource efficiency

Figure 2 presents the economy-based resource efficiency for different cases excluding the SDE+ subsidy. The stand-alone PLA plant and the biobased cluster have a much higher economy-based resource efficiency than the co-firing of biomass. This is due to the production of two value-added products PLA and bioethanol. The resource efficiency of the stand-alone PLA plant, excluding the SDE+ subsidy, is slightly lower than the biobased cluster. The joint ref.I and ref.II have a lower economy-based resource efficiency than the biobased cluster. This is due to the requirement of a much larger amount of wood pellets in case of the joint references (10.3 PJ), compared to the biobased cluster (2.8 PJ). In the latter case the difference between 10.3 PJ and 2.8 PJ wood pellets has been fulfilled by lignin. Besides, in case of the biobased cluster a large investment for the CHP plant has been avoided. According to these results, the economy-based resource efficiency seems a suitable measure for evaluating the value chains based on biorefinery/ cascading principle.

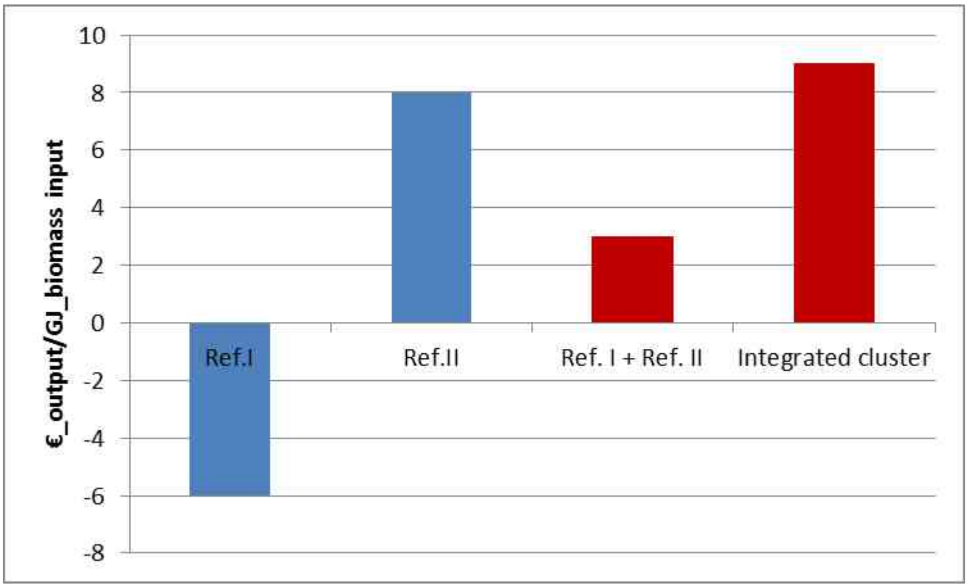

Figure 2: Economy-based resource efficiency for different cases excluding the SDE+ subsidy

Environmental-based resource efficiency

For the calculation of the environmental-based resource efficiency the net avoided $CO_{2\text{-eq}}$ emissions of each case has been compared to its fossil alternative. Figure 3 presents the environmental-based resource efficiency for different cases at an NL-el-mix. The results show that the environmental-based resource efficiency of the joint Ref. I and Ref. II is higher than the integrated cluster, due to a higher contribution of renewable heat and electricity in the former case. The highest efficiency belongs to the Ref. I, converting biomass to renewable electricity.

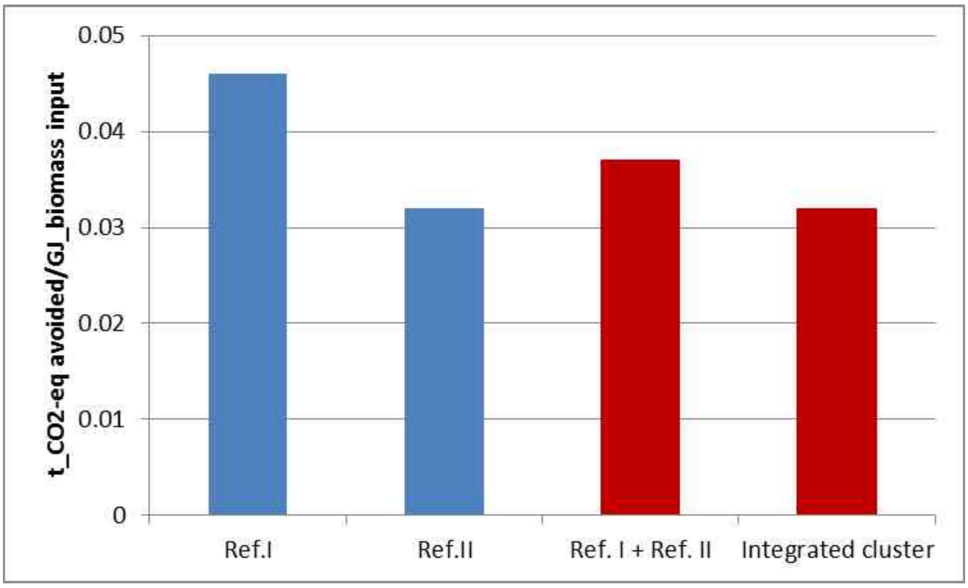

Figure 3: Environmental-based resource efficiency for different cases at NL-el-mix

Policy recommendations

The resource efficiency concept and the related indicators

The resource efficiency concept has been introduced and the need for more resource efficient use of biomass has been highlighted in a number of policy documents. However, what resource efficiency means and how it can be measured in concrete terms has not been laid down yet. This can result in different interpretations by different stakeholders and as a consequence, setting the right policy framework may become challenging.

Based on the analysis of the considered resource efficiency indicators within this study, the cases with a higher contribution of bioenergy perform better with respect to the energy-based and environmental-based resource efficiency, while biorefinery/cascading cases with a higher contribution of value-added products perform better with respect to the economy-based resource efficiency.

The energy-based resource efficiency does not take the quality of the final energy and produced materials into account. This indicator, therefore, is not a suitable measure for evaluating the value chains based on biorefinery/cascading principle. The economy-based resource efficiency on the other hand needs to be carefully interpreted. A sole focus on the market value can be misleading. We recommend that this criterion should also consider the generation costs and focus on the financial gap rather than on the market value of a product.

The environmental-based resource efficiency requires a careful analysis and definition of fossil-based alternatives to biobased products.

This study has focused on only one case study and the related criterion. Further research is essential focusing on many other cases and criteria to provide a sufficient basis for policy making.

Role of existing bioenergy policy support instruments on the profitability of an integrated biorefinery concept

The significance of biorefineries has been continuously recognised and supported through RD&D efforts, for instance under H2020. This case study has shown, that an integrated biobased cluster can lead to economic benefits and efficient use of biomass resources. Current bioenergy support instruments like the double counting measure for 2nd generation biofuels, as well as the SDE+ subsidy for renewable heat and electricity can indeed contribute to the profitability of integrated biorefinery concepts. However, lactic acid fermentation based on lignocellulosic biomass is still at the TRLs 3 to 5 (applied research/large-scale prototype). In other words, this innovative technology is not expected to become full commercial before 2020-2023. During this period support measures like investment subsidy could be helpful for further development of this technology.

Future role of biomass co-firing in an integrated biorefinery concept

Although biomass co-firing is an important option for achieving the Dutch RE targets in 2020 and 2023, the continuation of the SDE+ for co-firing after 2023 is uncertain. Alternatively, lactic acid production based on lignocellulosic biomass is expected to become full commercial after 2020-2023. Such an integrated biobased cluster could then offer the opportunity to deliver (partly) much cheaper biomass than wood pellets for co-firing. After 2020-2023 the support scheme for biomass co-firing could be revised in a way to promote biorefinery/cascading principle as well. This could be done by, e.g. lowering the level of subsidy for co-firing, so that it would become difficult, if not impossible, to use expensive biomass resources for this application.

1 Introduction

1.1 Biobased cluster at the Port of Rotterdam

The Biomass Policies project [1], supported by the Intelligent Energy Europe (IEE) programme, aims to improve the policy framework for the mobilisation of indigenous bioenergy value chains in contributing to the 2020 renewable energy targets and beyond. The project pays particular attention to competition in different sectors for the available biomass, resource efficiency and sustainability.

Resource efficiency has been defined as "producing more with less while avoiding environmental impacts [2]". Different than the other renewable energy sources biomass, when utilized unsustainably, can cause significant socio-economic and environmental implications. It is, therefore, particularly important to consider resource efficiency principles when developing integrated polices for bioenergy.

Biorefinery/cascading systems can play a key role in this process through refining the high quality fractions of biomass for high quality products, and the low quality fractions of biomass for energy. Biorefineries are defined as promising integrated approach for the co-production of both value-added products (bio-materials, bio-chemicals, bio-plastics, food, feed) and bioenergy (biofuels, biogas, heat and/or electricity) [3].

This case study focuses on a specific integrated biorefinery concept with the ambition to contribute to the discussions around resource efficient use of biomass and to the development of integrated policies that promote resource efficient use of biomass in Europe. The specific objectives of the case study are to:

- Discuss the resource efficiency concept and some of its proposed indicators in a concrete case and provide recommendations on this;
- Analyse the possible role of existing bioenergy policy support instruments on the profitability of an integrated biorefinery concept;
- Discuss the possible future role of biomass co-firing in an integrated biorefinery concept.

The considered case study is based on the integration of bioethanol/polylactic acid (PLA) production and the co-firing of biomass in a coal-fired power plant at the Port of Rotterdam. The Port of Rotterdam has a promising potential for bioenergy and biochemicals/bio-materials activities, as outlined in Annex I.

1.2 Contents of the report

The methodology used to compare different bioenergy and biorefinery options, handled in this study, is presented in Chapter 2.

The following three cases have been considered:

- Co-firing of wood pellets (Reference I);
- Stand-alone PLA plant (Reference II);
- Biobased PLA-co-firing cluster.

These cases are described in Chapter 3, after which the production cost of their main products (either electricity or PLA) have been calculated and compared with their market value and among each other. In order to assess the effect of relevant input parameters on the production cost of the main products, a number of sensitivity analyses have been performed and presented in Chapter 3, and in more detail in Annex IV.

In Chapter 4 attention has been directed towards the resource efficiency of the above-mentioned cases. Three indicators have been considered, namely the energy-based, the economy-based, and the environmental-based resource efficiency.

Finally, some policy recommendations are presented in Chapter 5.

2 Methodology

The methodology used in this case study is based on a biorefinery model, developed by ECN, within the FP7 project Bioref-Integ [4]. Based on the mass, energy and economic data of a process, the production costs of the main product for both a reference case, as well as for an integrated biorefinery scheme are calculated, with the objective to evaluate to what extent the integrated biorefinery scheme could enhance the economic competitiveness of the main product, compared to the reference case.

In this case study we have two reference cases:
- Ref. I: A biomass co-firing plant;
- Ref. II: A stand-alone PLA plant.

In case of the co-firing plant, electricity is the main product. All the variable and fixed costs will be divided by the total annual electricity production, in order to calculate the production cost of electricity from co-firing of wood pellets in €/MWh_{el}.

In case of the stand-alone plant, PLA is the main product. All the variable and fixed costs will be divided by the total annual PLA production, in order to calculate the production cost of PLA from wood chips in €/t_{PLA}.

The considered biobased cluster integrates the two reference cases. PLA will be the main product, and its production cost will be calculated in the same way as mentioned above for the stand-alone plant.

The calculated electricity production cost for the co-firing reference case will then be compared with the SDE+ subsidy parameters [5], while the calculated production cost for the produced PLA will be compared with the market value for PLA.

For the calculation of the GHG emissions, data from GEMIS LCA tool [6] have been used (see Annex V).

3 Three cases

3.1 Reference I: Co-firing of wood pellets

One of the SDE+ categories is the new capacity for co-firing of wood pellets in the coal-based power plants that were built in recent years (Figure 4). Table 1 presents the techno-economic parameters for this category. We assume an average net electric power of 900 MW_e for this study, resulting in a biomass contribution of 180 MW_e. Table 2 presents the SDE+ subsidy parameters for this category.

Figure 4: Block diagram reference I: co-firing of wood pellets

Table 1: Techno-economic parameters new capacity for biomass co-firing [5]

Parameters reference installation	Unit	Value
Net electric power of power plant	MW_e	700-1100
Co-firing ratio (based on energy output)	%	20
Full load hours E-production	h/a	7000
Efficiency biomass-based power plant	%	44
Subsidy duration	years	8
Specific investment biomass co-firing	€/kWe	450
O&M costs biomass co-firing	€/MWh_{el}	3

Table 2: Subsidy parameters new capacity for biomass co-firing [5]

	Unit	Advice 2015
Base rate	€/MWh_{el}	115
Correction rate ((provisionally) market price electricity 2015)	€/MWh_{el}	43
SDE+ subsidy	€/MWh_{el}	72

The main product of the co-firing plant is electricity. In order to calculate the production cost of electricity, all the variable and fixed costs have been divided by the total annual electricity production, with results presented in Table 3.

Table 3: Total production cost of electricity for Reference I: co-firing

	Unit	Value
Net electric power from biomass	MWh_{el}/a	1,260,000
Required biomass	€/MWh_{el}	77
Total investment biomass co-firing	€/MWh_{el}	8
Additional O&M costs biomass co-firing (on biomass MWh)	€/MWh_{el}	3
Total production cost of electricity from biomass co-firing	€/MWh_{el}	88

Under the system boundaries taken in this study, the production cost of electricity is 88 €/MWh_{el}, while the 2015 market price was estimated at 43 €/MWh_{el}. The difference – i.e. 45

€/MWh$_{el}$ – is the subsidy required for a zero Net Present Value (NPV). The difference between the SDE+ subsidy of 72 €/MWh$_{el}$ and 45 €/MWh$_{el}$ should cover the loan interest (5.5%), the return on equity (12%), and the inflation (2%), as assumed within SDE+ [5].

The required biomass contributes to 88% of the production cost (see Table 3). Figure 15 presents the effect of biomass cost on the production cost of electricity. In order to come to a zero NPV without any subsidy, the wood pellets cost should decrease to about 40% of the current cost (at constant values for other assumptions), i.e. 67 €/tonne compared to 160 €/tonne, which is unlikely to happen.

3.2 Reference II: Stand-alone PLA plant

In the stand-alone PLA plant 1 million tonne (d.m.) of wood chips will be converted to 600 kt of C5/C6 sugars and 300 kt of lignin. It is assumed, that the C5/C6 stream will be separated, before downstream processing on a 50/50 basis[1]. 300 kt of C5 sugars will be fermented into 190.000 m^3 of ethanol, and 300 kt of C6 sugars will be used for LA/PLA production[2]. The scope of the Port of Rotterdam ends with the production of ethanol and delivery of C6 sugars, the latter to be converted into 225 kt of PLA [8]. Table 4 presents the assumptions made for this system boundary.

Table 4: Techno-economic parameters for the PoR system boundary (lies at the C6 sugar/lignin streams) [8]

Parameter	Unit	Value
Input wood chips	Mt (d.m.)	1
Annual operation	hour	7500
Depreciation	yr	15
Sugar production	kt/a	600
C5 sugars (to ethanol fermentation)	kt/a	300
C6 sugars (to LA/PLA production)	kt/a	300
Lignin[3]	kt (d.m.)/a	300
Investment cost	M€	500
O&M costs (5% of investment cost)	M€	25
Electricity requirement	MW$_e$	35
	MWh	262,500
Heat requirement	MW$_{th}$	225[4]
	MWh	1,687,500

[1] It is assumed, that 1 Mt (d.m.) of wood chips will result in 600 kt of C5/C6 sugars (on a 50/50 basis) and 300 kt of lignin. A conversion efficiency of 90% for the hydrolysis process has been assumed, which means that 67 kt of cellulose would remain unconverted and will end at the lignin stream, together with 33 kt of ash. This unconverted cellulose can be used, like lignin, to generate heat and electricity. This is, however, not taken into account in this study. In other words, more heat and power can be produced in ref. II case. Also, more electricity can be produced from lignin/cellulose stream in the biobased cluster case (see 3.3), which means that less additional wood pellets would be required in that case, with the related positive effects on the cost of PLA production and resource efficiencies for these cases.
[2] It should be mentioned, that the composition of woody biomass, especially with respect to C5/C6 ratio, will deviate in practice from the above-mentioned assumptions. Moreover, there are currently a lot of developments regarding the combined conversion of C5 and C6 sugars to PLA [7].
[3] An LHV value of 25 MJ/kg (d.m.) is considered for lignin [9, 10, 11].
[4] It is assumed that part of this heat has been used to dry the lignin stream. If this is not the case, additional heat would be required, increasing the cost of PLA production in ref. II and biobased cluster cases (see 3.3). Also the resource efficiencies for these cases would slightly decrease. It is, however, not expected that this would have a major effect on the outcomes of the study.

For this case study, in order to come to a total process of converting wood chips to end products, we have added two sections to the system boundary of the Port of Rotterdam:

1. The required process for converting C6 sugars to PLA;
2. A combined heat and power (CHP) installation to produce heat and electricity from lignin.

A block diagram of the total process, i.e. reference II: stand-alone PLA plant, is presented in Figure 5.

Our assumptions regarding the production of PLA are summarized in Table 5. The amount of PLA produced (225 kt) is between 60% to 70% of the current global production of lactic acid, and about 30% of the projected lactic acid volumes in 2020 (see Annex II). The PoR has assumed a sugar-to-PLA conversion efficiency of 75%. The annual operation hours of the PLA plant is assumed to be 7500, equal to the full-load hours of the CHP installation. The depreciation period for the PoR system boundary is 15 years. In practice, however, the lifetime of the system could be longer, for example 20 years. Assumptions regarding capital cost, electricity and heat requirements are described in Annex III. Fixed costs, including labour, are assumed to be equal to 5% of the capital cost.

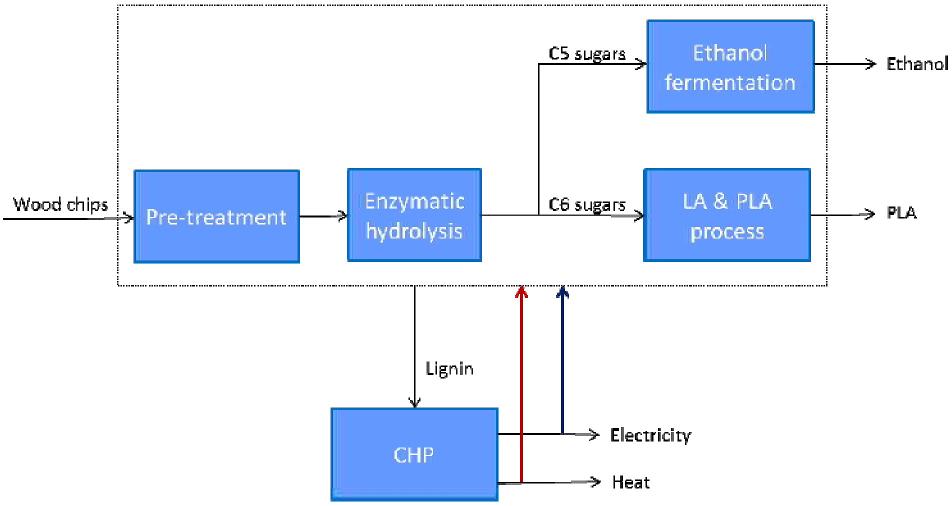

Figure 5: Block diagram reference II: stand-alone PLA plant

Table 5: Techno-economic data for PLA production from C6 sugars: Case PoR

Parameter	Unit	Value
Reference capacity	ktPLA/a	225 [8]
Conversion efficiency sugar-to-PLA	%	75% [8]
Annual operation	hr	7500
Depreciation	yr	15 [8]
Capital cost	M€	226
Fixed costs (including labour)	M€	11.3
Electricity requirement	GJ/t_{PLA}	8.2
Heat requirement	GJ/t_{PLA}	8.3

The thermal conversion of biomass in a combined heat & power plant within a range of 10 to 100 MW_e is one of the SDE+ categories, with the related assumptions presented in Table 6. Table 7 presents the SDE+ subsidy parameters for this category. For the case of PoR the same electrical and thermal efficiencies have been considered as for the reference SDE+ (14%, resp. 74%). Other assumptions are also the same as for the reference SDE+.

A comparison between the produced heat and power by the CHP installation (Table 6) and the total process auxiliaries shows, that the total heat and power requirements are higher than the total production. We assume, that the required heat and power will be purchased, while the produced heat and power will be sold, both at their market value.

Table 8 presents the cost of PLA production, excluding SDE+ subsidy, for the reference II: stand-alone plant. For comparison also the market values of PLA (low and high) are given. Based on the assumptions made, this reference case is economically feasible, even without an SDE+ subsidy for the CHP installation.

Table 6: Techno-economic parameters thermal conversion of biomass; SDE+ reference [5], resp. Case PoR

Parameter	Unit	Assumption SDE+ [1]	Assumption Case PoR
Scale SDE+ category	MW_e	10 - 100	-
Thermal input	MW_{th}	68	278
Full load hours E/H-production	h/a	7500	7500
Electrical power	MW_e/MWh	9.5/71,250	39/292500
Heat output	MW_{th}/MWh	50/375,000	204/1,530,000
Max. electrical efficiency	%	14	14
Subsidy duration	year	12	12[5]
Investment costs	€/kW_{th}_input	1840	1840
	M€	125	511
Fixed O&M costs	€/kW_{th}_input	110	110
	M€	7.5	31

Table 7: SDE+ subsidy parameters thermal conversion of biomass, 10-100 MW_e [5]

	Unit	Advice 2015
Base rate	€/MWh	84
Correction rate	€/MWh	23
Subsidy	€/MWh	61

Table 8: Cost of PLA production for Reference II: stand-alone PLA plant (excluding SDE+ subsidy)

	Unit	Value
PLA production	t/a	225,000
Softwood chips	€/t PLA	556
Bioethanol (2nd generation, including double counting)	€/t PLA	-595
Electricity requirement	€/t PLA	345
Heat requirement	€/t PLA	173
Market value heat and electricity produced	€/t PLA	-186

[5] In this study we have assumed different depreciations for different cases or different sections of a case: for biomass co-firing 8 years, equal to subsidy duration; for CHP plant 12 years, also equal to subsidy duration; and for the PoR system boundary and the LA/PLA production plant 15 years. This, however, is not expected to have a major effect on the outcomes of the study.

Investment costs PoR system boundary (lies at the C6 sugar/ lignin streams)	€/t PLA	148
Other costs / O&M PoR system boundary (lies at the C6 sugar/ lignin streams)	€/t PLA	111
Investment costs CHP	€/t PLA	189
O&M costs CHP	€/t PLA	136
Investment costs sugar-to-PLA plant	€/t PLA	67
O&M costs sugar-to-PLA plant	€/t PLA	50
Cost of PLA production excluding SDE for CHP installation	€/t PLA	995
Market value PLA (low)	€/t PLA	1700
Market value PLA (high)	€/t PLA	3000

This reference case is an example of a biorefinery and cascading principle, in which wood chips are converted to bio-material (PLA), biofuel (bioethanol), heat and electricity. Wood chips have the highest contribution to the production cost of PLA, followed by the cost of auxiliaries, costs of the CHP (investment + O&M), costs of the PoR system boundary and the PLA plant (see Table 8).

The market value of the produced 2nd generation bioethanol has the highest effect in lowering the production cost of PLA, followed by the market value for the produced heat and power. This order, however, would change when we take the SDE+ subsidy for the produced heat and electricity into account.

Figure 6 shows the different production chains for PLA, while Figure 7 presents the technology readiness levels (TRLs) of different sections of the PLA production chains [12]. As can be seen, lactic acid production from fermentation of sugars from sugar crops or starch crops are at full commercial application (TRL 9), while lactic acid production based on lignocellulosic biomass is still at the TRLs 3 to 5 (applied research/large-scale prototype). In other words, it still takes time before this technology would become full commercial.

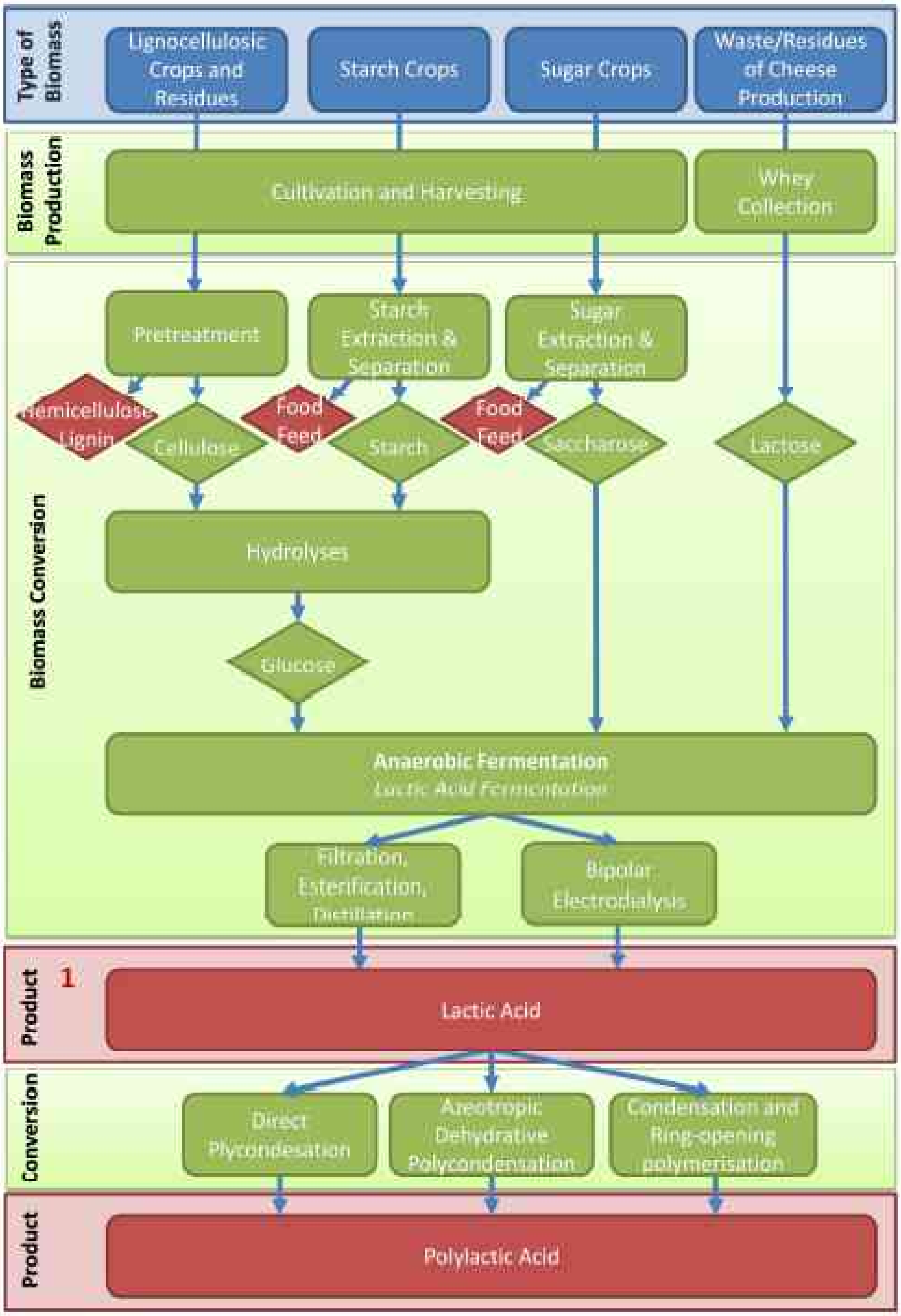

Figure 6: PLA production chain [12]

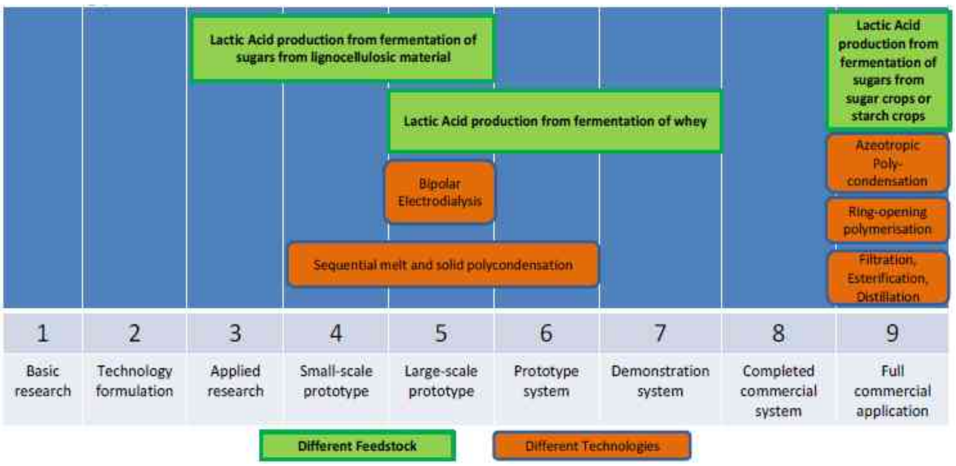

Figure 7: Technology Readiness Levels of different sections of PLA production chains [12]

3.3 Biobased PLA-co-firing cluster

In this case the two references, described in Section 3.1 and Section 3.2, are integrated into a biobased PLA-co-firing cluster. Figure 8 presents a block diagram of this biobased cluster.

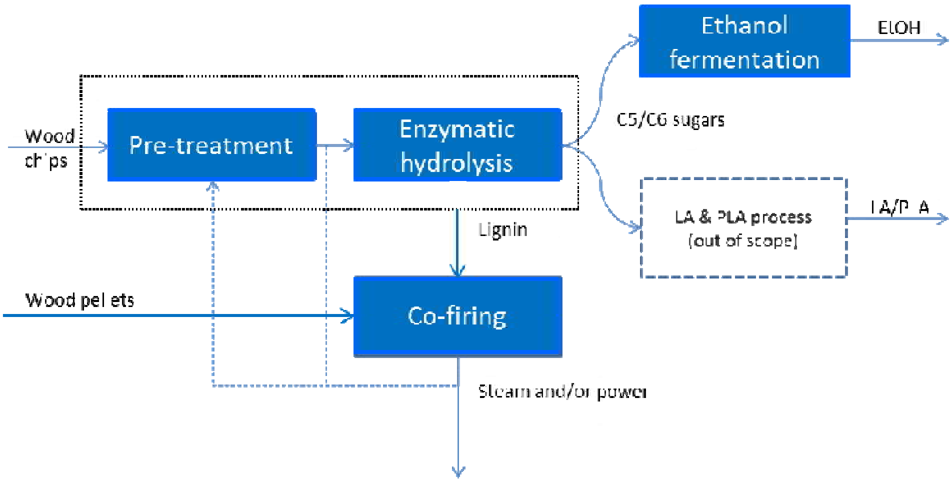

Figure 8: Block diagram integrated biobased PLA-co-firing cluster

All the techno-economic assumptions for this integrated case are the same as the assumptions made for the described references in the previous sections, with two exceptions:

1. In comparison to reference I (co-firing plant), more than 70% of the wood pellets are replaced by the lignin fraction of the wood chips. Therefore, only less than 30% of the wood pellets are still required to produce the same amount of electricity as in the reference I.
2. In comparison to reference II (stand-alone PLA plant), the existing co-firing plant will replace the CHP installation. In this way, a large investment of about 40% of the total investment for the reference II will be avoided.

Table 9 presents the cost of PLA production, excluding SDE+ subsidy, for the integrated biobased PLA-co-firing cluster. For comparison also the market values of PLA (low and high) are given.

Based on the assumptions made, this integrated case is economically feasible, even without an SDE+ subsidy for co-firing. This is a major advantage of this case compared to reference I, in which co-firing of biomass seems to remain dependent on subsidy, even in the future. Compared to reference II, the production cost of PLA is 20% lower (800 versus 1000 €/t PLA). This is mainly due to the difference in investment costs of the CHP installation and the co-firing plant, followed by a higher value for the produced electricity via co-firing, compared to the value of combined heat and electricity production via CHP. On the other hand, the cost of required wood pellets is an additional expense compared to reference II (see Table 9).

A question that arises regarding this biobased cluster is the future of SDE+ subsidy for biomass co-firing in the Netherlands. Although this option is important for achieving the Dutch RE targets in 2020 and 2023, the continuation of the SDE+ for co-firing after 2023 is uncertain. On the other hand, lactic acid production based on lignocellulosic biomass is expected to become full commercial after 2020-2023 (see Figure 7). Such an integrated biobased cluster could then offer the opportunity to deliver (partly) much cheaper biomass than wood pellets for co-firing. In absence of a co-firing plant the available lignin, depending on the location, availability of a heat source, technological development, could either be combusted in a biomass CHP plant, be sold as a fuel, or it can be used in lignin chemistry.

Table 9: Cost of PLA production for the integrated biobased PLA-co-firing plant (excluding SDE+ subsidy)

	Unit	Value
PLA production	t/a	225,000
Softwood chips	€/t PLA	556
Bioethanol (2nd generation, including double counting)	€/t PLA	-595
Electricity requirement	€/t PLA	345
Heat requirement	€/t PLA	173
Required input wood pellets	€/t PLA	118
Market value electricity produced	€/t PLA	-241
Investment costs PoR system boundary (lies at the C6 sugar/ lignin streams)	€/t PLA	148
Other costs / O&M PoR system boundary (lies at the C6 sugar/ lignin streams)	€/t PLA	111
Specific investment biomass co-firing	€/t PLA	45
Additional O&M costs biomass co-firing (on biomass MWh)	€/t PLA	17
Investment costs sugar-to-PLA plant	€/t PLA	67
O&M costs sugar-to-PLA plant	€/t PLA	50
Cost of PLA production excluding SDE	€/t PLA	794
Market value PLA (low)	€/t PLA	1700
Market value PLA (high)	€/t PLA	3000

3.4 Sensitivity analysis

In order to assess the effect of relevant input parameters on the production cost of the main products, a number of sensitivity analyses have been performed. The following input parameters have been considered:

- Cost of biomass;
- Investment cost of CHP;
- Market price of 2nd generation bioethanol;
- Conversion efficiency of C6 sugars to PLA;
- Conversion efficiency of C5 sugars to ethanol.

None of the performed variations have led to a higher PLA production cost than its market value. This, however, might be the case by a combination of parameter variations, but in general, the positive outcome for the integrated system seems quite robust.

The results of the sensitivity analysis are summarised below. More detailed information can be found in Annex IV.

3.4.1 Cost of biomass

Cost of biomass, i.e. wood pellets and/or wood chips has been varied from 50% to 150% of the reference value for three considered cases. As a result:

- The production cost of electricity for Ref. I will change to 56% resp. 127% of the cost in the reference case. Even at the lowest wood pellets cost, the production cost is higher than the market price for electricity.
- The production cost of PLA will be 73% to 127% of the cost for the Ref. II, and 59% to 141% of the cost for the biobased cluster.

3.4.2 Investment cost of CHP

Varying the investment cost of the CHP installation for the Ref. II case from 50% to 150% of the reference value leads to 15% decrease or increase of the production cost for PLA.

3.4.3 Market price of 2nd generation bioethanol

It is uncertain whether the double counting regulation would continue to exist after 2020. We have, therefore, compared the reference situation including double counting for the stand-alone PLA plant and the integrated case, with situations in which the market price for 2nd generation bioethanol equals that of 1st generation bioethanol, or even equals the market price of gasoline (see Table 25). Such variations lead to increase of the production cost for PLA up to:

- 17% resp. 34% for the stand-alone PLA plant;
- 21% resp. 42% for the integrated case.

3.4.4 Conversion efficiency of C6 sugars to PLA

For each 5% variation in the conversion efficiency of C6 sugars to PLA, the production cost of PLA will change for 5% in case of the Ref. II, and 8% for the integrated cluster.

3.4.5 Conversion efficiency of C5 sugars to ethanol

Conversion efficiency of C5 sugars to ethanol has indirectly been varied for the stand-alone PLA plant and the integrated case, by decreasing the volume of ethanol produced by 10%, resp. 20%. For each 10% decrease in the volume of produced ethanol the production cost of PLA will decrease for about 6% for the stand-alone PLA plant and 8% for the integrated case.

4 Resource efficiency

Biomass value chains touch on a multitude of sectors and topics which makes them much more complicated than other fields. This also implies a complexity to guarantee sustainability over the full value chain. Resource efficiency aims at a more productive use of resources over their life cycle, and using resources in a sustainable way, within the planet's long term boundaries [13].

In this study we use the following three indicators to evaluate the resource efficiency of the considered value chains:

1. Energy-based resource efficiency: net energy output per unit biomass;
2. Economy-based resource efficiency: net value added per unit biomass;
3. Environmental-based resource efficiency: net CO_2 avoided per unit biomass.

The following general equations are applied:

$$\textit{Energy-based Resource Efficiency} = \frac{\begin{gathered}[\text{Ethanol production } (GJ_{LHV}) + \text{PLA production } (GJ_{LHV}) + \text{Electricity production } (GJ) + \text{Heat production } (GJ) \\ - \text{Electricity consumption } (GJ) - \text{Heat consumption } (GJ)]\end{gathered}}{\text{Biomass input } (GJ\_LHV)}$$

$$\textit{Economy-based Resource Efficiency} = \frac{\begin{gathered}[\text{Ethanol production } (GJ) * \text{Value ethanol } \left(\tfrac{€}{GJ}\right) + \text{PLA production } (GJ) * \text{Value PLA } \left(\tfrac{€}{GJ}\right) + \text{Electricity production } (GJ) * \\ \text{Value electricity } \left(\tfrac{€}{GJ}\right) + \text{Heat production } (GJ) * \text{Value heat } \left(\tfrac{€}{GJ}\right) - \text{Electricity consumption } (GJ) * \text{Value electricity } (€/GJ) \\ - \text{Heat consumption } (GJ) * \text{Value heat } \left(\tfrac{€}{GJ}\right) - \text{Biomass input } (GJ) * \text{Value biomass } \left(\tfrac{€}{GJ}\right) - \text{Investment costs } \left(\tfrac{€}{a}\right) - \text{fixed} \\ \text{O and M costs } (€/a)]\end{gathered}}{\text{Biomass input } (GJ\ LHV)}$$

$$\textit{Environmental-based Resource Efficiency} = \frac{\text{Net avoided } CO2 \text{ eq emissions } (t)}{\text{Biomass input } (GJ\_LHV)}$$

The focus in this chapter is on the comparison of resource efficiency of the joint reference I and reference II with the resource efficiency of the biobased cluster. For the completeness, however, we have also calculated the resource efficiencies of each of the reference cases.

4.1 Energy-based resource efficiency

Table 10 presents the resource inputs (in GJ) and product outputs (in GJ) of the three considered cases. Table 11 and Figure 9 present the energy-based resource efficiency (in GJ/GJ) for the different cases.

Table 10: Resource inputs and product outputs of the three considered cases (in GJ)

	Unit	Value
Input		
Ref.I: co-firing plant		
Wood pellets	GJ	10,309,000
Ref. II: stand-alone PLA plant		
Wood chips	GJ	18,889,000

Electricity requirement	GJ	2,795,000
Heat requirement	GJ	7,945,000
Integrated PLA-co-firing cluster		
Wood pellets	GJ	2,809,000
Wood chips	GJ	18,889,000
Electricity requirement	GJ	2,795,000
Heat requirement	GJ	7,945,000
Output		
Ref.I: co-firing plant		
Electricity production	GJ	4,536,000
Ref. II: stand-alone PLA plant		
PLA	GJ	4,048,000
Bioethanol (2nd generation)	GJ	4,009,000
Heat & electricity production	GJ	6,563,000
Integrated PLA-co-firing cluster		
PLA	GJ	4,048,000
Bioethanol (2nd generation)	GJ	4,009,000
Electricity production	GJ	4,536,000

Table 11: Energy-based resource efficiency for different cases

	Unit	Value
Ref.I: co-firing plant	GJ/GJ_{input}	0.44
Ref. II: stand-alone PLA plant	GJ/GJ_{input}	0.21
Ref.I + Ref.II	GJ/GJ_{input}	0.29
Integrated PLA-co-firing cluster	GJ/GJ_{input}	0.09

The results presented in Table 11 show that:

- The co-firing plant (ref. I) has the highest energy-based resource efficiency, followed by the stand-alone PLA plant (ref. II) and the biobased cluster.
- The joint ref. I and ref. II has higher energy-based resource efficiency than the biobased cluster.

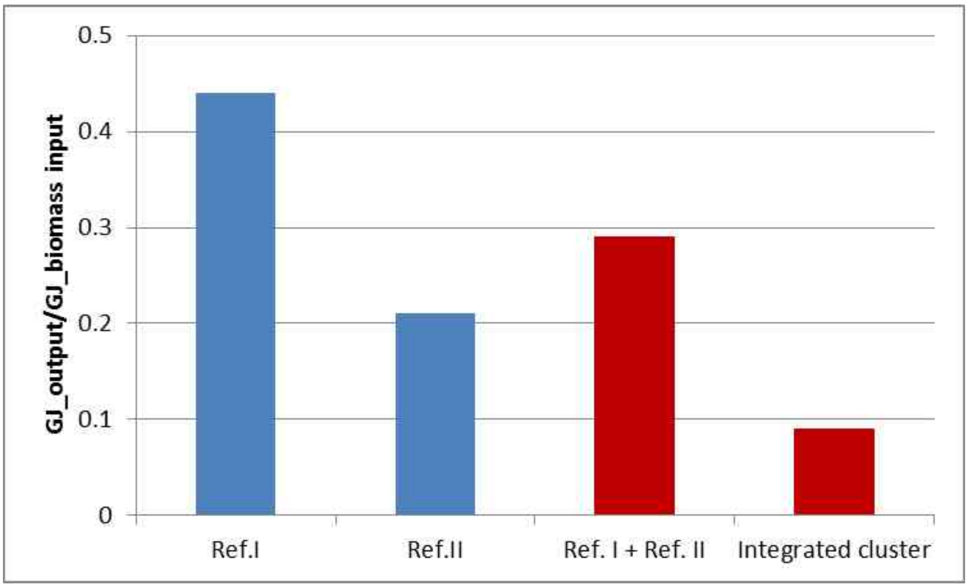

Figure 9: Energy-based resource efficiency for different cases

The main reason for such an order in the resource efficiency of the cases is, that this indicator does not take the quality of the final energy and produced materials into account. There is no difference between 1 GJ of heat (no matter whether it is high quality steam or hot water) and 1 GJ of electricity, or bioethanol, or PLA. Based on this indicator, a final product like heat, which is at the bottom of the value pyramid, will have the highest energy-based resource efficiency. Of course the production of bio-materials with much more process steps, compared to heat and/or power production, will lead to a lower overall energy-based resource efficiency. This indicator, therefore, is not a suitable measure for evaluating the value chains based on biorefinery/cascading principle.

4.2 Economy-based resource efficiency

Table 12 presents the inputs and outputs of the three considered cases per annum. For the produced heat and electricity two values are presented: one based on the market prices and the other based on the SDE+ base rates. Table 13 and presents the economy-based resource efficiency (in €/$GJ_{\text{LHV-biomass input}}$) for the different cases, excluding as well including the SDE+ subsidy.

Based on the results presented in Table 13 and Figure 10, the stand-alone PLA plant and the biobased cluster have a much higher economy-based resource efficiency than the co-firing of biomass. This is due to the production of two value-added products PLA and bioethanol. The resource efficiency of the stand-alone PLA plant, excluding the SDE+ subsidy, is slightly lower than the biobased cluster. The joint ref.I and ref.II have a lower economy-based resource efficiency than the biobased cluster. This is due to the requirement of much larger amount of wood pellets in case of joint references (10.3 PJ), compared to the biobased cluster (2.8 PJ). In the latter case the difference between 10.3 PJ and 2.8 PJ wood pellets has been fulfilled by lignin. Besides, in case of the biobased cluster a large investment for the CHP plant has been avoided.

According to the results discussed above, economy-based resource efficiency seems a suitable measure for evaluating the value chains based on biorefinery/cascading principle.

Table 12: Inputs and outputs (per annum) of the three considered cases

	Unit	Value
Input		
Ref.I: co-firing plant		
Wood pellets	GJ	10,309,000
Wood pellets	€	97,027,000
Investment costs	€	10,125,000
Fixed O&M costs	€	3,780,000
Ref. II: stand-alone PLA plant		
Wood chips	GJ	18,889,000
Wood chips	€	125,000,000
Investment costs	€	91,030,000
Fixed O&M costs	€	66,883,000
Electricity requirement	€	53,111,000
Heat requirement	€	37,591,000
Integrated PLA-co-firing cluster		
Wood pellets	GJ	2,809,000
Wood chips	GJ	18,889,000
Wood pellets	€	125,000,000
Wood chips	€	26,439,000
Investment costs	€	58,517,000
Fixed O&M costs	€	40,108,000
Electricity requirement	€	53,111,000
Heat requirement	€	37,591,000
Output		
Ref.I: co-firing plant		
Electricity production	€	54,180,000 (excl. SDE+) / 144,900,000 (incl. SDE+)
Ref. II: stand-alone PLA plant		
PLA	€	382,296,000
Bioethanol (2nd generation)	€	133,874,000
Heat & electricity production	€	41,927,000 (excl. SDE+) / 153,125,000 (incl. SDE+)
Integrated PLA-co-firing cluster		
Electricity production	€	54,180,000 (excl. SDE+) / 144,900,000 (incl. SDE+)
PLA	€	382,296,000
Bioethanol (2nd generation)	€	133,874,000

Table 13: Economy-based resource efficiency for different cases

	Unit	Value excl. SDE+	Value incl. SDE+
Ref.I: co-firing plant	€/GJ_{input}	-6	3
Ref. II: stand-alone PLA plant	€/GJ_{input}	8	14
Ref.I + Ref.II	€/GJ_{input}	3	10
Integrated PLA-co-firing cluster	€/GJ_{input}	9	14

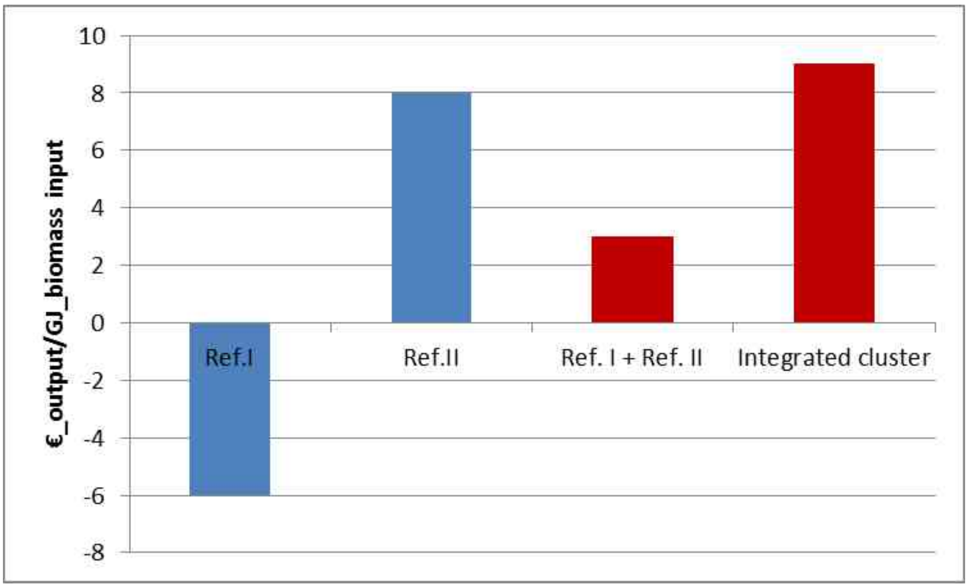

Figure 10: Economy-based resource efficiency for different cases excluding the SDE+ subsidy

4.3 Environmental-based resource efficiency

4.3.1 Life cycle analysis of the PoR cases

For the calculation of the GHG emissions, data from GEMIS LCA tool [6] have been used (see Annex V). The GHG emissions of the PoR cases are compared among each other, based on the following system boundaries:

- Ref.I: the co-firing plant
  - Delivers reference electricity output (4.54 PJ);
  - Delivers no heat, but also requires none, i.e. no balancing;
  - Delivers no PLA, i.e. balanced with fossil PS[6];
  - Delivers no EtOH, i.e. balanced with fossil gasoline.
- Ref. II: the stand-alone PLA plant
  - Delivers no net electricity output, i.e. balanced with either the EU-el-mix, or the NL-el-mix;
  - Delivers less heat than internally needed, i.e. balanced with gas boiler;
  - Delivers reference outputs of both PLA and EtOH (225 kt, respectively 4.01 PJ).

[6] This approach was taken in a German study on biomaterials (see [14] and [15]).

- The integrated PLA-co-firing cluster
  - Delivers no net electricity output, i.e. balanced with either the EU-el-mix, or the NL-el-mix;
  - Delivers no heat, therefore the internally needed heat is balanced with gas boiler;
  - Delivers reference outputs of both PLA and EtOH (225 kt, respectively 4.01 PJ).

Table 14 presents the input/output data of the cases for GHG calculations. Table 15 presents the GHG balance of the three cases. Higher GHG balances are reached for the Ref. II and the Integrated cluster when using NL-el-mix instead of EU-el-mix. The lowest GHG balance at NL-el-mix belongs to the Ref. I, followed by the Integrated cluster.

Table 14: Input/output data of the cases for GHG calculations

	Unit	Value	Comment
Ref.I: co-firing plant			
Wood pellets input	PJ	10.31	US import
Electricity output	PJ	4.54	
PS output	kt	225	Balance from fossil
Gasoline output	PJ	4.01	Balance from fossil
Ref. II: stand-alone PLA plant			
Wood chips	PJ	18.89	EU import (DE)
Electricity requirement	PJ	2.79	
Heat requirement	PJ	7.94	
Electricity output	PJ	1.05	
Heat output	PJ	5.51	
PLA output	kt	225	
Bioethanol output	PJ	4.01	
Integrated PLA-co-firing cluster			
Wood pellets	PJ	2.81	US import
Wood chips	PJ	18.89	EU import (DE)
Electricity requirement	PJ	2.79	
Heat requirement	PJ	7.94	
PLA output	kt	225	
Bioethanol output	PJ	4.01	

Table 15: GHG balance for the PoR cases

	Unit	Value (EU-el-mix)	Value (NL-el-mix)
Ref.I: co-firing plant	$t_{CO2\ eq}$	1,211,000	1,211,000
Ref. II: stand-alone PLA plant	$t_{CO2\ eq}$	1,133,000	1,424,000
Integrated PLA-co-firing cluster	$t_{CO2\ eq}$	1,213,000	1,342,000

When comparing the GHG emissions of the integrated PLA-co-firing cluster with the emissions of REF I + REF II, the reference outputs of both PLA and EtOH will remain unchanged (225 kt, respectively 4.01 PJ). However, the reference electricity output will be the sum of power generated via co-firing (4.54 PJ) as well as via the CHP (1.05 PJ). Table 16 presents the GHG balance of the integrated cluster and the joint balance of the Ref. I and Ref. II. The former has a slightly lower GHG emissions than the latter.

Table 16: GHG balance comparison of Ref. I + Ref. II with integrated cluster

	Unit	Value (EU-el-mix)	Value (NL-el-mix)
Ref.I + Ref. II	$t_{CO2\ eq}$	1,328,000	1,619,000
Integrated PLA-co-firing cluster	$t_{CO2\ eq}$	1,319,000	1,497,000

4.3.2 Environmental-based resource efficiency of PoR cases

While in case of the LCA analysis the GHG emissions of the PoR cases were compared among each other, for the calculation of the environmental-based resource efficiency we have calculated the net avoided $CO_{2\text{-eq}}$ emissions of each case compared to its fossil alternative. Table 17 presents the avoided $CO_{2\text{-eq}}$ emissions for different options. The environmental-based resource efficiency for different cases is presented in Table 18 and Figure 11. The results show that both the avoided $CO_{2\text{-eq}}$ emissions, as well as the environmental-based resource efficiency of the joint Ref. I and Ref. II are higher than the integrated cluster, due to a higher contribution of renewable heat and electricity in the former case. It can also be seen, that the co-firing plant at an NL-el-mix has a much better performance than at an EU-el-mix.

Table 17: Avoided $CO_{2\text{-eq}}$ emissions for different cases

	Unit	Value (EU-el-mix)	Value (NL-el-mix)
Ref.I: co-firing plant	$t_{CO2\text{-eq avoided}}$	261,000	471,000
Ref.I + Ref. II	$t_{CO2\text{-eq avoided}}$	948,000	1,077,000
Ref. II: stand-alone PLA plant	$t_{CO2\text{-eq avoided}}$	687,000	606,000
Integrated PLA-co-firing cluster	$t_{CO2\text{-eq avoided}}$	607,000	688,000

Table 18: Environmental-based resource efficiency for different cases

	Unit	Value (EU-el-mix)	Value (NL-el-mix)
Ref.I: co-firing plant	$t_{CO2\text{-eq avoided}}/GJ_{input}$	0.025	0.046
Ref. II: stand-alone PLA plant	$t_{CO2\text{-eq avoided}}/GJ_{input}$	0.036	0.032
Ref.I + Ref.II	$t_{CO2\text{-eq avoided}}/GJ_{input}$	0.032	0.037
Integrated PLA-co-firing cluster	$t_{CO2\text{-eq avoided}}/GJ_{input}$	0.028	0.032

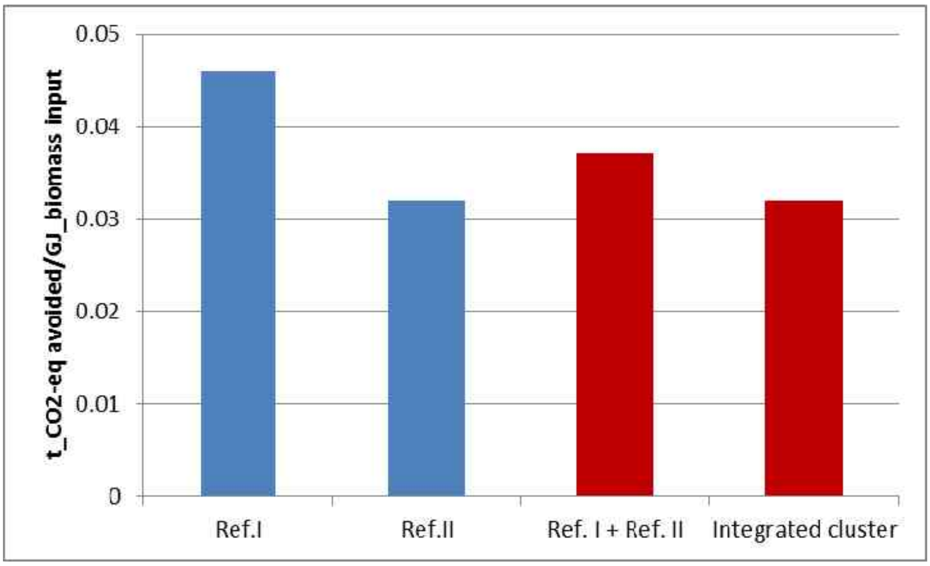

Figure 11: Environmental-based resource efficiency for different cases at NL-el-mix

5 Policy recommendations

The resource efficiency concept and the related indicators

The resource efficiency concept has been introduced and the need for more resource efficient use of biomass has been highlighted in a number of policy documents. However, what resource efficiency means and how it can be measured in concrete terms has not been laid down yet. This can result in different interpretations by different stakeholders and as a consequence, setting the right policy framework may become challenging.

Based on the analysis of the considered resource efficiency indicators within this study, the cases with a higher contribution of bioenergy perform better with respect to the energy-based and environmental-based resource efficiency, while biorefinery/cascading cases with a higher contribution of value-added products perform better with respect to the economy-based resource efficiency.

The energy-based resource efficiency does not take the quality of the final energy and produced materials into account. This indicator, therefore, is not a suitable measure for evaluating the value chains based on biorefinery/cascading principle. The economy-based resource efficiency on the other hand needs to be carefully interpreted. A sole focus on the market value can be misleading. We recommend that this criterion should also consider the generation costs and focus on the financial gap rather than on the market value of a product. The environmental-based resource efficiency requires a careful analysis and definition of fossil-based alternatives to biobased products.

This study has focused on only one case study and the related criterion. Further research is essential focusing on many other cases and criteria to provide a sufficient basis for policy making.

Role of existing bioenergy policy support instruments on the profitability of an integrated biorefinery concept

The significance of biorefineries has been continuously recognised and supported through RD&D efforts, for instance under H2020. This case study has shown, that an integrated biobased cluster can lead to economic benefits and efficient use of biomass resources. Current bioenergy support instruments like the double counting measure for 2^{nd} generation biofuels, as well as the SDE+ subsidy for renewable heat and electricity can indeed contribute to the profitability of integrated biorefinery concepts. However, lactic acid fermentation based on lignocellulosic biomass is still at the TRLs 3 to 5 (applied research/large-scale prototype). In other words, this innovative technology is not expected to become full commercial before 2020-2023. During this period support measures like investment subsidy could be helpful for further development of this technology.

Future role of biomass co-firing in an integrated biorefinery concept

Although biomass co-firing is an important option for achieving the Dutch RE targets in 2020 and 2023, the continuation of the SDE+ for co-firing after 2023 is uncertain. Alternatively, lactic acid production based on lignocellulosic biomass is expected to become full commercial after 2020-2023. Such an integrated biobased cluster could then offer the opportunity to deliver (partly) much cheaper biomass than wood pellets for co-firing. After 2020-2023 the support scheme for biomass co-firing could be revised in a way to promote biorefinery/cascading principle as well. This could be done by, e.g. lowering the level of subsidy for co-firing, so that it would become difficult, if not impossible, to use expensive biomass resources for this application.

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Annex 1: The Port of Rotterdam [16]

The port of Rotterdam accommodates the world's largest industrial cluster that uses biomass as raw material. Here, biobased companies benefit from endless possibilities for the supply of all conceivable forms of biomass and the distribution of finished products. The presence of a strong petrochemical cluster and the knowledge and experience of the existing biobased industry make Rotterdam an attractive business location.

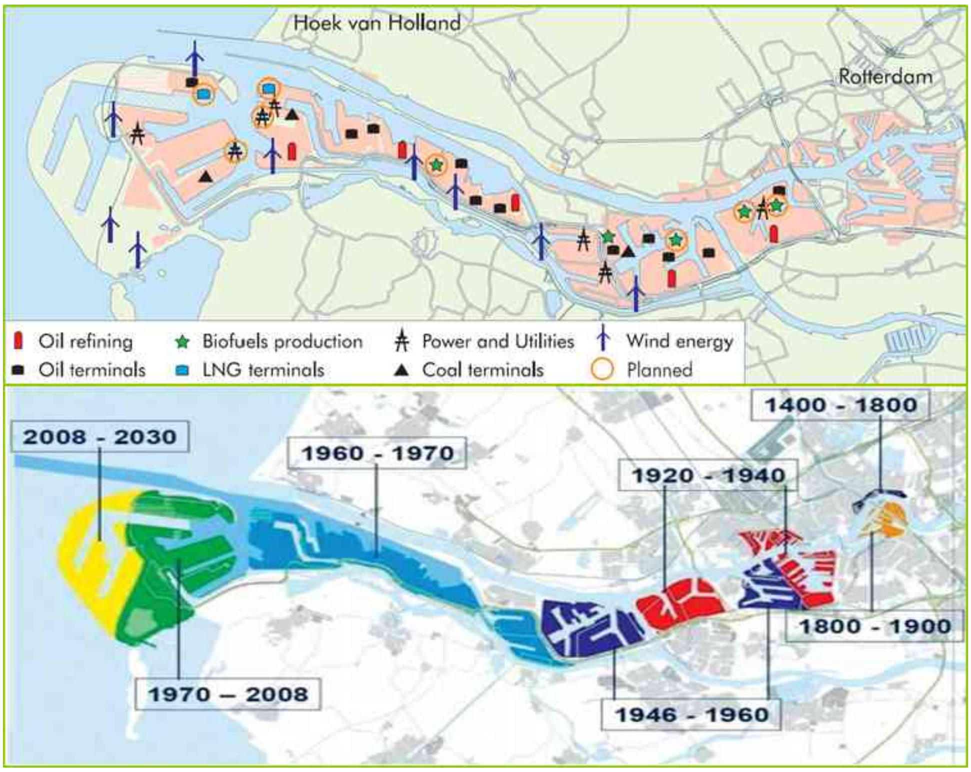

Figure 12: Map of Port of Rotterdam; above: energy facilities; below: changes over time (yellow area: Maasvlakte 2) [17]

Biofuels

In the port of Rotterdam, the production, trade, storage and transhipment of biofuels come together. The port is ideally situated for the supply of raw materials and biofuels from around the world. The same applies to the distribution of biofuels across Europe. With five manufacturers of biodiesel, bio-ethanol and renewable diesel, the port of Rotterdam is a major biofuel producer for the European market.

Biochemistry

45 chemical companies, five oil refineries, four palm oil refineries, five biofuel producers, two biochemical factories and various power stations together form a strong industrial cluster in the port of Rotterdam. The port area of Rotterdam has room for new chemical and biobased companies.

Bioenergy

The port of Rotterdam is an attractive location for sustainable energy production from biomass. The port offers logistical advantages for the supply of raw materials. Co-firing biomass in power stations is an important way to reduce CO_2 emissions in energy generation.

The new coal-fired power stations of Engie (formerly GdF Suez) and Uniper (formerly EON) on the Maasvlakte are both capable of co-firing 20% to 30% biomass.

The biomass co-fired in coal-fired power stations usually consists of imported wood chips, but residual materials, for example from the biobased chemical industry, can also play a part. Over the long term, wood chips are expected to increasingly serve as a raw material for the biobased industry in the port of Rotterdam. Maasvlakte 2 offers possibilities for establishing new biobased industry. Businesses which use biomass as raw material can build production locations there.

Figure 13: Maasvlakte 2 refers to the overall expansion of the Port of Rotterdam. This is the entire port area as it will look when MVII is completed [18]

Annex II: General assumptions

Feedstocks

Two types of wood have been used: wood pellets and wood chips.

Wood pellets

Wood pellets are the reference biomass for the co-firing option within SDE+ [5]. Assumptions regarding energy content and costs of wood pellets are presented in Table 19.

Table 19: Assumptions regarding energy content and costs of wood pellets [5]

	Unit	Value
Energy content	GJ/tonne	17
Total costs	€/tonne / €/GJ	160 / 9.4
Market price	€/tonne	135
Risk premium	€/tonne	15
Transport	€/tonne	10

Wood chips

Wood chips are the reference biomass for the case study at the Port of Rotterdam [8]. Assumptions regarding composition (d.m.), energy content and costs of wood chips are presented in Table 20.

Table 20: Assumptions regarding composition (d.m.), energy content and costs of wood chips [8]

	Unit	Value
Composition:		
(Hemi)cellulose	Wt._d.m.%	67%
Lignin	Wt._d.m.%	30%
Ash	Wt._d.m.%	3%
Energy content	GJ/t_d.m.	19
Total costs	€/t / €/GJ	125 / 6.6
Market price	€/t	120[7]
Risk premium	€/t	0
Transport	€/t	5[8]

Products

Depending on the configuration of the considered systems, one or more of the following products would be produced:

- Bioethanol
- Polylactic acid (PLA)
- Heat & electricity via CHP plant
- Electricity via co-firing plant.

Bioethanol

It is assumed, that the produced C5/C6 stream will be separated, before downstream processing on a 50/50 basis. C5 sugars will be fermented into ethanol and C6 sugars will be used for LA/PLA production [8]. Assumptions regarding energy content and value of bioethanol are presented in Table 21.

Table 21: Assumptions regarding energy content and value of bioethanol

	Unit	Value
LHV ethanol	MJ/L_a.r.	21.1
Value bioethanol 1st generation	€/L	0.5[9]
	€/GJ	23.7
Value gasoline	€/GJ	14.0
Value bioethanol 2nd generation[10]	€/GJ	33.4

PLA

Lactic acid has a market volume of around 300-400 kt/year, with a market price of 1000-1200 €/tonne [19]. Lactic acid has the potential to grow considerably in terms of market volume. A significant increase in volume is projected for the years to come to 800 kt in 2020 [19].

[7] FOB dry matter; FOB: F(ree) O(n) (B)oard = paid up to the side of the dock in Rotterdam including ocean freight, but excluding any terminal handling charges or any cost that would be incurred after [8]

[8] Off loading of vessel and transport by belt [8]

[9] 40-63 €/hL [4]

[10] Including double counting

PLA has been originally an expensive polymer (> € 50/kg), which was mainly used in biomedical industry. Through the development of efficient bulk polymerisation processes is PLA currently one of the cheapest biobased plastics with a price of 1700 to 3000 €/tonne, depending on specific quality (grade) and producer. This relatively low price of PLA, which in recent years has also been stable, has made switching to biobased polymers more attractive for many companies[11] [20].

Heat & electricity via CHP plant

One of the categories of the SDE+ is the thermal conversion of biomass in a combined heat & power plant within a range of 10 to 100 MW_e. The base rate and the subsidy for the produced heat & power in this category are 84 €/MWh_{el} and 61 €/MWh_{el} respectively [5] (see also Chapter 3).

Electricity via co-firing plant

Another SDE+ category is the new capacity for co-firing of biomass in the coal-based power plants that were built in recent years. The base rate and the subsidy for the produced electricity in this category are 115 €/MWh_{el} and 72 €/MWh_{el} respectively [5] (see also Chapter 3).

Auxiliaries

Both the stand-alone PLA plant, as well as the biobased PLA-co-firing cluster require heat and power for their different unit operations. In practice, the required heat and power would be delivered by either a CHP installation (in case of stand-alone plant), or the co-firing plant (in case of the biobased cluster).

The required heat is assumed to be purchased at a price of 4.90 €/GJ, equivalent to 70% of the long-term average Dutch TTF gas price[12]. The required electricity is assumed to be purchased at 100 €/MWh_{el}.

[11] It is expected, that in the future the lower grade PLA would have to compete with the bulk polymers like polyethylene [21]. An average current market price for different polyethylene grades (HDPE, LDPE, LLDPE) equals to about 800 €/tonne (based on the market prices of these products in 2014 [22, 23, 24], multiplied by the ratio between the current oil price and the oil price in 2014.

[12] Source: ICEndex

Annex III: Data PLA plant

Investment cost

Purac has reported about the construction of a lactide plant in Thailand producing monomer for bioplastics [25]. The investment cost for this 75,000 tonnes lactide plant is estimated at M€ 45. In another reference [26] Corbion Purac announces the intension to invest in a 75,000 tonnes PLA plant in Thailand, with an estimated capex of M€ 60.

Based on the above-mentioned data, the investment cost for a 75,000 tonnes sugar-to-PLA plant is estimated to be M€ 105. In case of the PoR, however, the assumed production capacity for the C6-sugar-to-PLA plant is 225,000 tonnes. Using the 0.7 scaling factor results in an investment cost of M€ 226 for such a plant at the PoR.

Electricity and heat requirements

Vink & Davies [27] have reported on the life cycle inventory and impact assessment regarding the Ingeo™ PLA production. Figure 14 presents the primary energy from non-renewable resources for the total Ingeo production system and per production step. The last three steps concern the primary energy from non-renewable resources, to be converted into the process utilities (heat and electricity), for the production of PLA from dextrose.

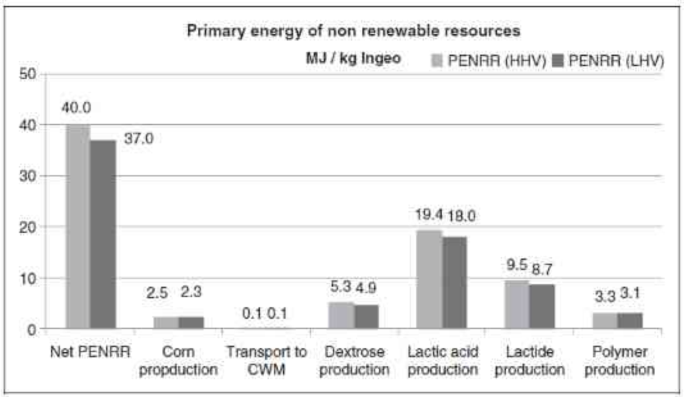

Figure 14: Primary energy from non-renewable resources for the total Ingeo production system and per production step [27]

Table 22 presents these three values with a total of 29.8 MJ_{LHV}/kg_{PLA}. We assume that this primary energy will be converted to about equal amount of final energy as heat and electricity. Assuming electrical and thermal efficiencies of 40%LHV, resp. 90%LHV, will result in the process electricity and heat requirement in GJ/t_{PLA}, as presented in the table.

Table 22: Electricity and heat requirement of the sugar-to-PLA plant

	Unit	Value
Primary energy of non-renewable resources		
Lactic acid production	MJ_{LHV}/kg_{PLA}	18.0
Lactide production	MJ_{LHV}/kg_{PLA}	8.7
Polymer production	MJ_{LHV}/kg_{PLA}	3.1

Total dextrose-to-PLA	MJ_{LHV}/kg_{PLA}	29.8
Assumed contribution to electricity	MJ_{LHV}/kg_{PLA}	20.6
Assumed contribution to heat	MJ_{LHV}/kg_{PLA}	9.2
Electrical efficiency	%LHV	40
Thermal efficiency	%LHV	90
Electricity requirement	GJ/t_{PLA}	8.2
Heat requirement	GJ/t_{PLA}	8.3

Annex IV: Sensitivity analysis

In order to assess the effect of relevant input parameters on the production cost of the main products, i.e. electricity in case of reference I and PLA in case of other two cases, a number of sensitivity analyses have been performed. The following input parameters have been considered:

- Cost of biomass;
- Investment cost of CHP;
- Market price of 2^{nd} generation bioethanol;
- Conversion efficiency of C6 sugars to PLA;
- Conversion efficiency of C5 sugars to ethanol.

Cost of biomass

Cost of biomass, i.e. wood pellets and/or wood chips has been varied from 50% to 150% for three considered cases. Table 23 summarizes the corresponding name and cost of biomass for these variations.

Table 23: Cost of biomass and name of the variations for three considered cases

Wood pellets €/GJ	Wood chips €/GJ	Ref.I: co-firing	Ref.II: stand-alone PLA	Integrated PLA-co-firing
4.7	3.3	WP50%	WC50%	WP/WC/50%
7.5	5.3	WP80%	WC80%	WP/WC/80%
9.4 (reference case)	6.6	WP100%	WC100%	WP/WC/100%
11.3	7.9	WP120%	WC120%	WP/WC/120%
14.1	9.9	WP150%	WC150%	WP/WC/120%

According to Figure 15 cost of wood pellets has a large effect on the cost of produced electricity. Varying the cost of wood pellets from 50% to 150% of the reference case, will lead to production costs for electricity equal to 56% resp. 127% of the cost in the reference case. Even at the lowest wood pellets cost, the production cost is higher than the market price for electricity.

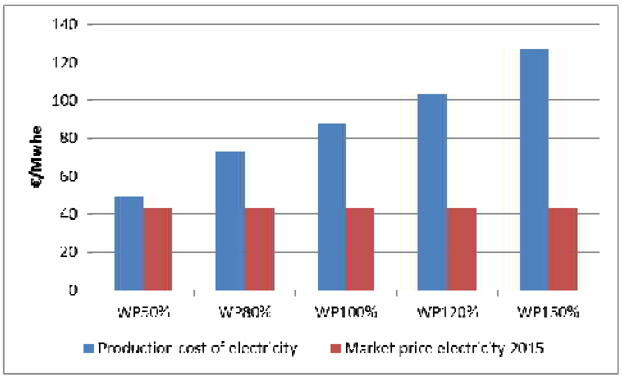

Figure 15: Effect of biomass cost on the production cost of electricity in case of the reference I

According to Figure 16 and Figure 17 varying the cost of wood chips and wood pellets from 50% to 150% of the reference case, will lead to production costs for PLA equal to:

- 73% to 127% of the cost for the reference II: stand-alone PLA;
- 59% to 141% of the cost for the biobased cluster.

In other words, biomass cost has a larger effect on biobased cluster than on ref. II.

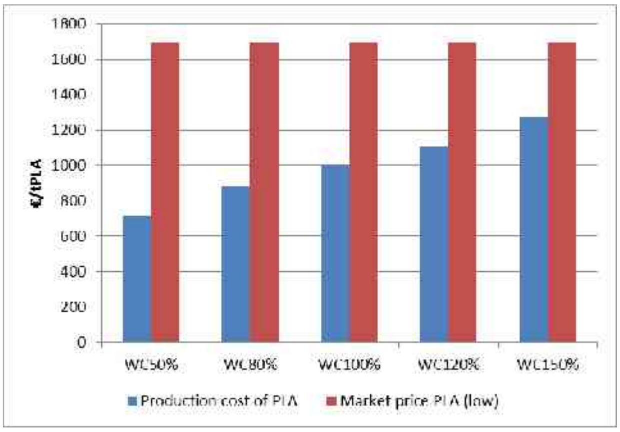

Figure 16: Effect of biomass cost on the production cost of PLA in case of the reference II

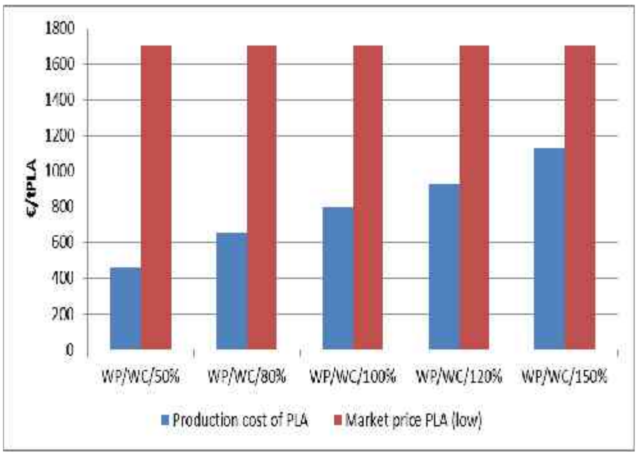

Figure 17: Effect of biomass cost on the production cost of PLA in case of the biobased cluster

Investment cost of CHP

The investment cost of the CHP installation has been varied from 50% to 150% for the reference II case. As the O&M cost is related to the investment cost (5% of investment), this cost will also vary from 50% to 150% of the reference value. Table 24 summarizes the corresponding name and investment/O&M costs for these variations. Such variations, according to Figure 18, lead to 15% decrease or increase of the production cost for PLA.

Table 24: Investment cost of CHP and name of the variations

Investment CHP €/kW$_{th}$_input	O&M CHP €/kW$_{th}$_input	Ref.II: stand-alone PLA
920	55	CHP50%
1840 (reference case)	110	CHP100%
2760	165	CHP150%

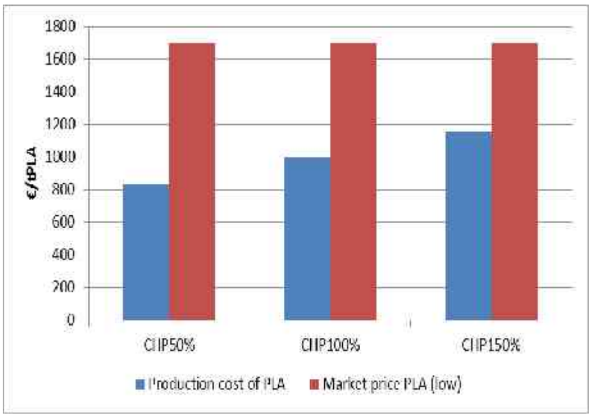

Figure 18: Effect of investment cost of CHP on the production cost of PLA

Market price of 2nd generation bioethanol

It is uncertain whether the double counting regulation would continue to exist after 2020. We have, therefore, compared the reference situation including double counting for the stand-alone PLA plant and the integrated case, with situations in which the market price for 2nd generation bioethanol equals that of 1st generation bioethanol, or even equals the market price of gasoline. Table 25 summarizes the corresponding name and market price for these variations. Such variations, according to Figure 19, lead to increase of the production cost for PLA up to:

- 17% resp. 34% for the stand-alone PLA plant;
- 21% resp. 42% for the integrated case.

Table 25: Market price of 2nd generation bioethanol and name of the variations

Market price €/GJ	Ref.II: stand-alone PLA/ Integrated PLA-co-firing
33.4 (reference case)	DC_incl
23.7	DC_excl_1st_gen
14.0	DC_excl_gasoline

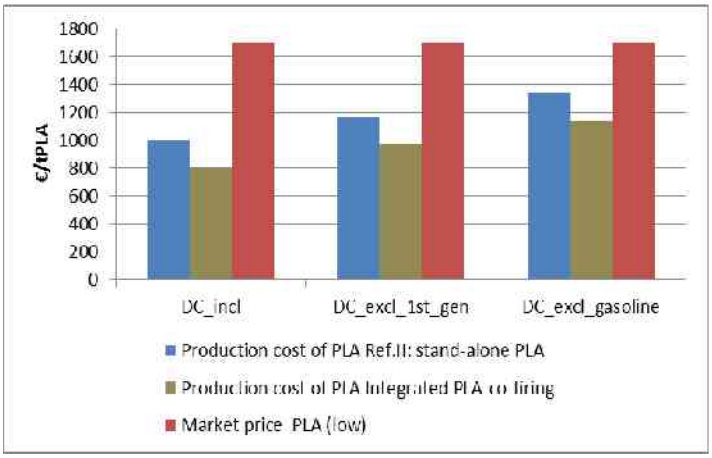

Figure 19: Effect of market price 2nd generation ethanol on the production cost of PLA

Conversion efficiency of C6 sugars to PLA

Conversion efficiency of C6 sugars to PLA has been varied from 65% to 80% for the stand-alone PLA plant and the integrated case. Table 26 summarizes the corresponding name and conversion efficiency for these variations. The production cost of PLA, according to Figure 20, will increase for about 5% for each 5% decrease in the conversion efficiency for both the stand-alone PLA plant, as well as for the integrated case.

Table 26: Conversion efficiency C6 sugars to PLA and name of the variations

C6 sugars to PLA	Ref.II: stand-alone PLA/ Integrated PLA-co-firing
65%	C6_PLA_65%
70%	C6_PLA_70%
75% (reference case)	C6_PLA_75%
80%	C6_PLA_80%

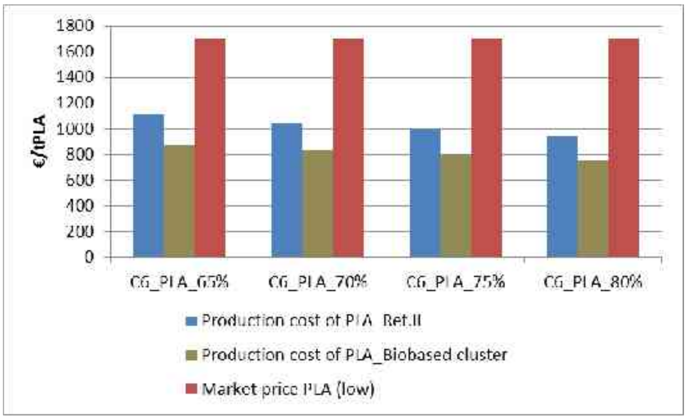

Figure 20: Effect of conversion efficiency C6-to-PLA on the production cost of PLA

Conversion efficiency of C5 sugars to ethanol

Conversion efficiency of C5 sugars to ethanol has indirectly been varied for the stand-alone PLA plant and the integrated case, by decreasing the volume of ethanol produced by 10%, resp. 20%. Table 27 summarizes the corresponding name and the volume of ethanol produced for these variations. The production cost of PLA, according to Figure 21, will increase for:

- about 6% for each 10% decrease in the volume of produced ethanol for the stand-alone PLA plant;
- about 8% for the same variation for the integrated case.

Table 27: Volume of ethanol production and name of the variations

Ethanol Ml/a	Ref.II: stand-alone PLA/ Integrated PLA-co-firing
190 (reference case)	100%ETOH
171	90%ETOH
152	80%ETOH

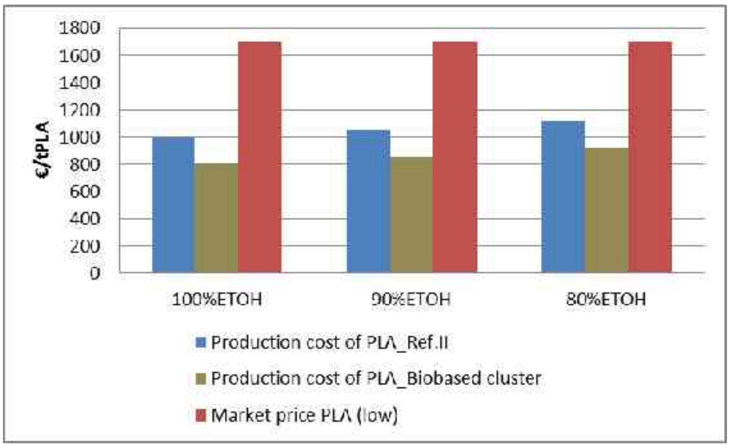

Figure 21: Effect of conversion efficiency C5-to-ethanol on the production cost of PLA

Annex V: LCA data GEMIS

Table 28: GEMIS 4.95 data for the PoR case study

	Unit	Value	Comment
Wood pellets (US import)	g CO_2.eq/MJ	19	Harvesting, pelletizing, shipment
Wood chips (EU import, DE)	g CO_2.eq/MJ	18	Harvesting, chipping, transport by truck
Natural gas boiler, NL	g CO_2.eq/MJ	68	Burnt in boiler
el. grid EU	g CO_2.eq/MJ	101	el-mix, no grid loss
el. Grid NL	g CO_2.eq/MJ	147[13]	el-mix, no grid loss
Gasoline, EU-mix (no bio)	g CO_2.eq/MJ	86	Burnt in car, no conversion loss
Polystyrene (PS)	kg/t	2973	Delivered, not burnt
Polystyrene (PS)	g CO_2.eq/MJ	86	Burnt after use

The CO_2 emissions from bioenergy systems can be separated into two components:

A. Life-cycle emissions: These are the emissions occurring due to biomass combustion and upstream processes (e.g. fossil fuel for harvesting, transport, processing)
B. C stock change emissions: These are CO_2 emissions from changes in forest carbon stocks, e.g. extraction of forest thinnings for bioenergy, and C absorption as the forest regrows. In the case of forest residues, a time series of emissions occurs if the residues were left to decay.

Component a) is fully included in the data used in this report. Component b) is an issue under intense discussion [28], [29], [30], [31]. It has been shown for Europe that GHG emissions resulting from C stock changes are between 0 and 4 g CO_2/MJ wood pellets from harvest residues, pre-commercial thinnings and thinning residues [32], i.e. they are far smaller than the life-cycle GHG emissions (around 20 g CO_2eq/MJ). Similarly, stem wood from thinnings would have close to zero CO_2 emissions for a 100 year time horizon. Yet, for other forest materials such as stem wood, GHG emissions from C stock changes could be in the order of 120 g CO_2/MJ for a 20-year time horizon [32].

[13] The share of renewable and nuclear electricity in the EU el-mix is higher than in the Netherlands' el-mix, while the share of natural gas and coal-based electricity in the Netherlands' el-mix is higher than in the EU el-mix.