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1 Introduction

The aim of the CLARA project is to develop a concept for production of advanced liquid biofuels based on chemical looping gasification (CLG) of different pre-treated biogenic residues. The project addresses the complete biomass-to-fuel chain, i.e. pre-treatment, gasification, syngas cleaning, fuel synthesis, and upgrading.

The objective of Task 7.1 in Work Package 7 is to determine costs for feedstock supply from the decentralized pre-treated biomass production plants at industrial scale for the downstream CLG plant (200 MW) for the investigated feedstocks, wheat straw and pine forest residue.

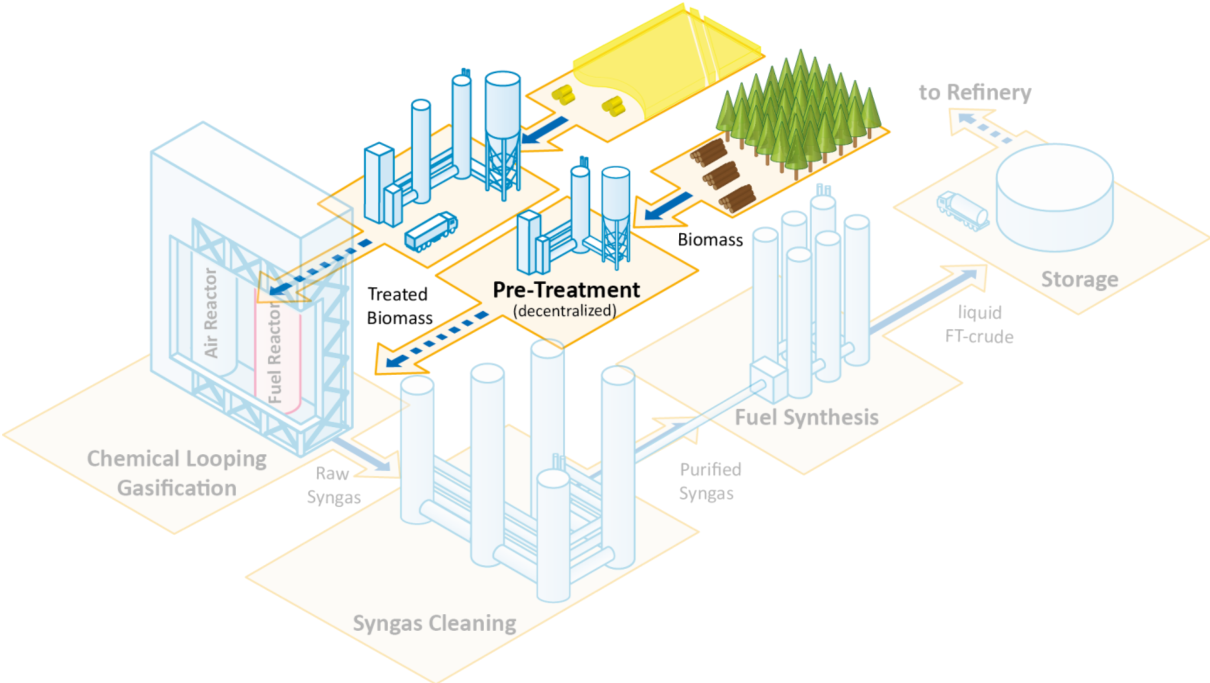

Figure 1 Schematic overview of the biomass-to-liquid process chain investigated in the CLARA project.

The methodology to elaborate the present deliverable, as summarized in Figure 2, has as starting point the information from the operational experience from CENER's pilot plant (Task 2.4) and is also based on up-scaling studies, production plant mass and energy balances (Task 1.4), and economic models (Task 1.4). A description of the pre-treatment concept including each step considered and energy and mass balances can be consulted in D1.4 "Layout of full-scale pre-treatment plant". The pre-treatment for each feedstock includes the following steps:

- Wheat straw (WS): chopping, pelleting and additivation
- Pine Forest Residue (PFR): chipping, drying and pelleting.

Based on the above mentioned information, the analysis of three representative locations in Europe, named as base case scenarios, was carried out. Grouping of base case scenarios was based on most impacting factors in the production cost, taking into account biomass availability among EU-28 countries, in order to calculate production cost as a function of pre-treatment plants scale size (production capacity).

In a second step, the supply cost was calculated. Several possible pre-treatment plant configurations, considering the number of plants and production capacities were evaluated, to clarify the impact of the supply model due to variability in the production cost related with this configuration. This approach allows to calculate a representative production cost (weighted average supply cost) for the possible de-centralized pre-treatments plants' configuration. Then, the transport cost was added to the supply cost. Transport cost was calculated based on feedstock availability, CLG pellet demand, and, in order not to affect market price, the share of available biomass consumed by the CLG plant.

Finally, the pellet cost development (supply cost including production and transport) was calculated for selected base case scenarios, depending feedstock price fixing the production capacities. This exercise allows to calculate minimum, maximum, and most probable (average) supply cost for pre-treated pellets and to compare the supply cost with historical data for spot prices from industrial wood pellets.

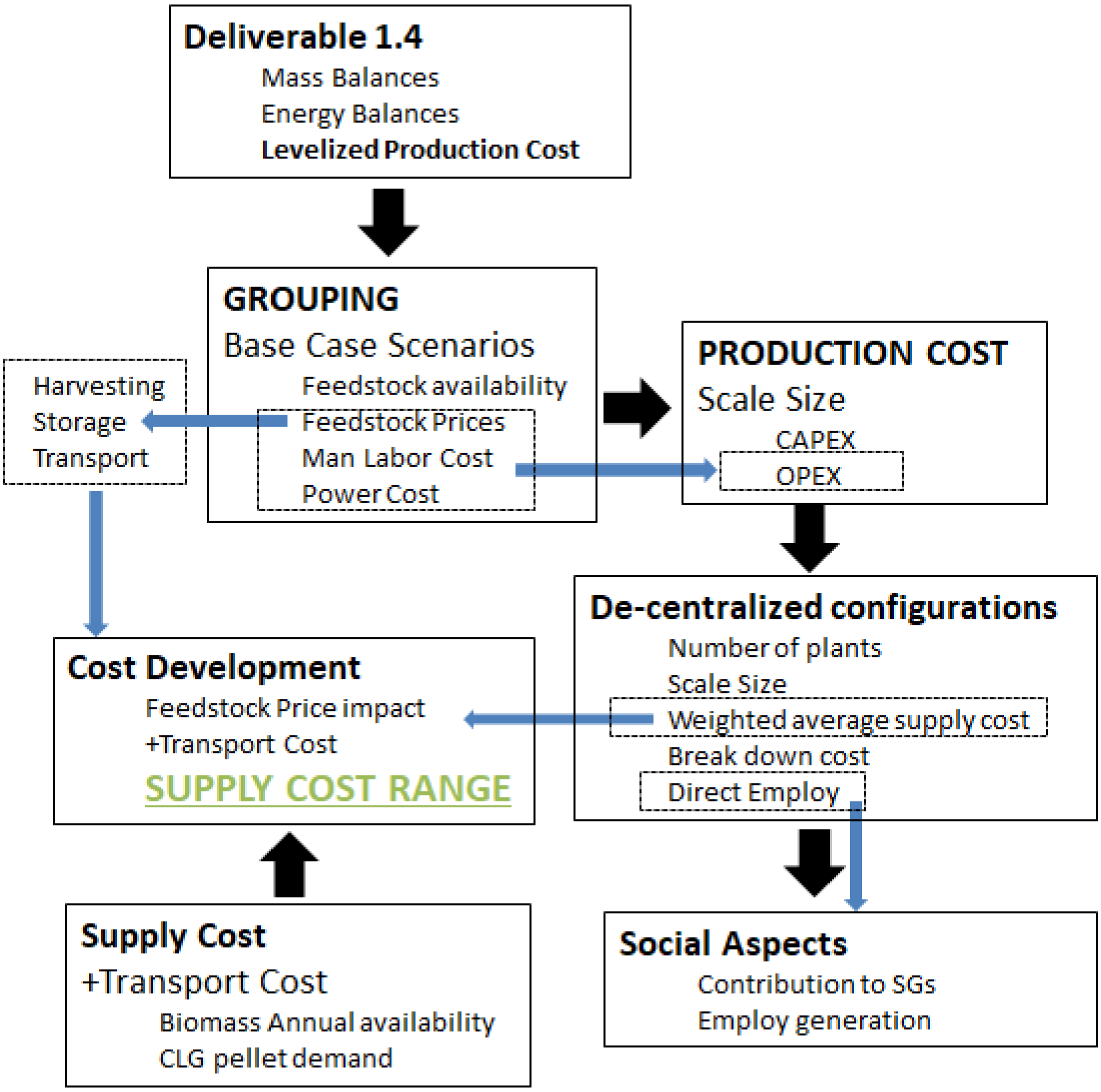

Figure 2 Methodology for pellet supply cost calculation

The last section, social aspects, summarizes the contribution to achieving the Sustainable Development Goals (SDGs) from the UN and the direct impact in rural areas in terms of direct employ generation as result from the evaluation and modelling of the possible de-centralized pre-treatment configurations.

2 Selection of base case scenarios

In order to have a comprehensive understanding of the possible feedstock supply cost, a selection of base case scenarios considering several factors was analysed. According to the breakdown price calculated in D1.4 “Layout of full-scale pre-treatment plant” with 180 kt/y capacity (input biomass), the main factors affecting production cost (Table 1) were raw feedstock price, man labour cost, and power cost. Therefore, the first step has been identifying variations among EU28 countries in order to establish base case scenarios.

Table 1 Breakdown production cost of selected feedstock in €/MWh for wheat straw (WS) and pine forest residue (PFR)

Cost (€/MWh)	WS	PFR
Feedstock	9.3	17.5
Maintenance & repair	0.4	0.4
Power	1.1	1.9
Man power	1.2	1.6
Manage & administration	0.1	0.2
Capital cost	0.4	0.7
Total	12.4	22.3

2.1 Feedstock availability and price

The analysis of feedstock availability for straw residues [1] [2] and forest residues [1] [3] in Europe shown the production potential of several locations. Concerning straw residues, the top countries are in order of potential (see Figure 3): France (FR), Germany (DE), Poland (PL), Romania (RO), Italy (IT) and Spain (ES). Total bio-economic potential of four agricultural residues (wheat straw, corn stover, barley straw and rapeseed straw) in the year 2030 predicted by Wietschel et al. [2] is in accordance with Join Research Centre (JRC) observations.

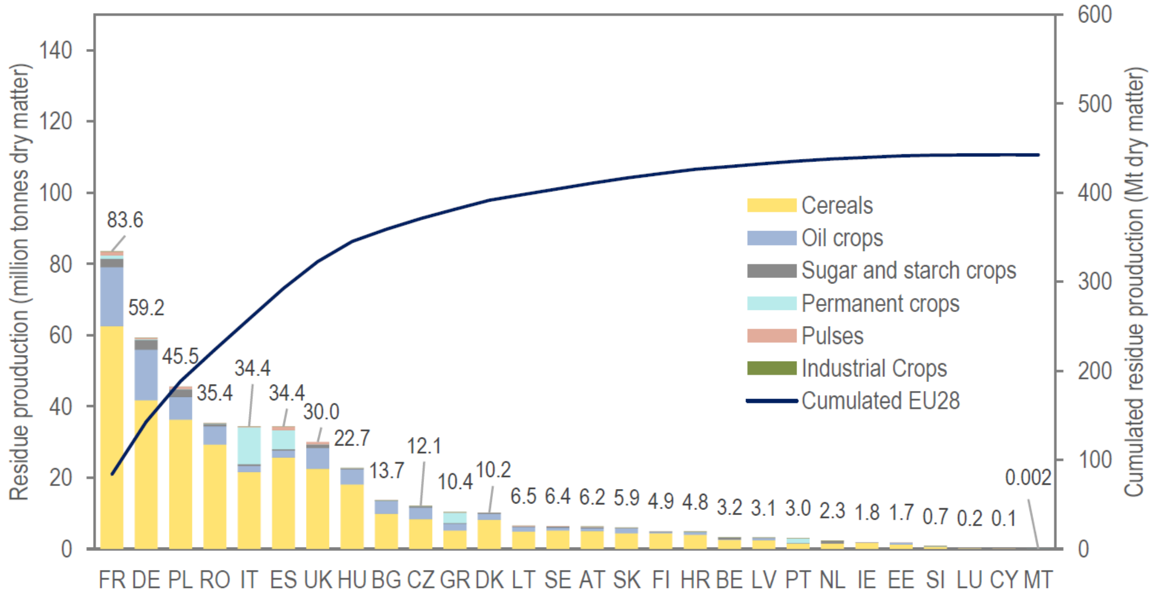

Figure 3 Residue production (top pane) from the main crop groups per member state, expressed in Mt of dry matter per year; and the shares at national level (bottom pane). Average values over the reference period 2006-2015. [1]

The main potential in EU28 for forest residues generation, such as pine and spruce, according to data from Join Research Centre (JRC) about harvesting [1] correspond to following countries: Sweden (SE), Germany (DE), Finland (FI), France (FR), Poland (PL) and Spain (ES). These data are also in agreement with the data from Bioenergy Europe about the evolution of forest area in EU28 Member States between 1990 and 2020 [3], since the maximum potential is located in Sweden (SE), Finland (FI), Spain (ES) France (FR), Germany (DE), Poland (PO), and Italy (IT) (Figure 4).

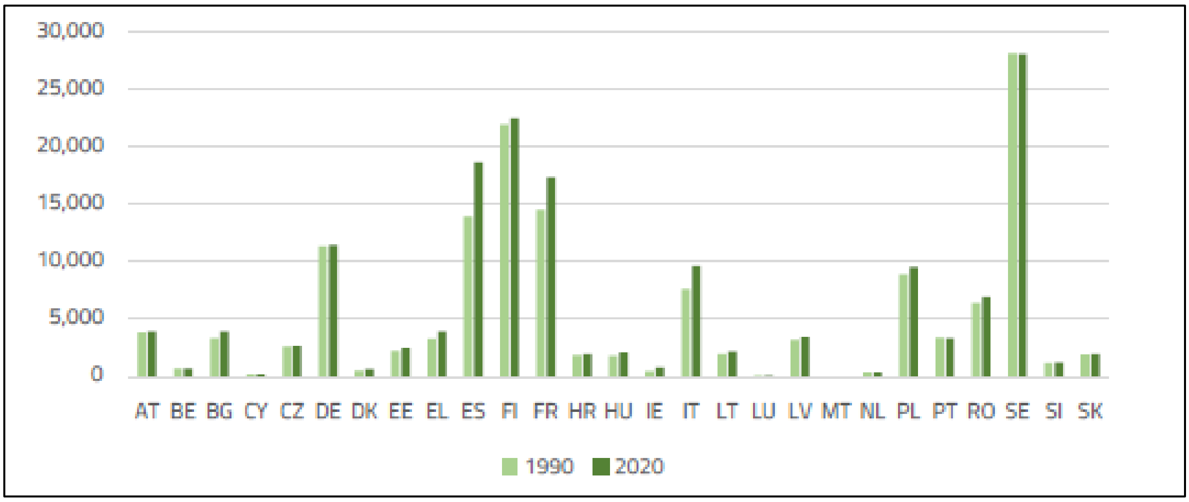

Figure 4 Evolution of available stock of forest in EU27 Member States between 1990 and 2020 (million m^3) [3]

Raw material cost including factors such as harvesting, handling, storage, or man labor cost have already been previously calculated by EU founded projects such as BIOCORE (FP7-241566 in 2012[4]) and BIOBOOST (FP7-282873 in 2013 [5]). The conclusion from the former project shows a dry wheat straw minimum price of approximately 29 €/t (Hungarian case) up to values of 40 €/t and market prices (ex-farm) up to 50 €/t. Minimal values reported by BIOCORE are between 32 and 36 €/t for countries like Finland, Germany, or Poland.

The BIOBOOST project reports more widespread values, ranging 25-80 €/t, for forest residues. The price in the case of Spain, France, or Italy depends on the slope where the forest residue is harvested (<20% or >20%) and the country with values from 47 €/t up to 87 €/t. For countries from Central and East Europe, the reported values are in the case of energy wood between 54 € and 81 € per dry ton.

2.2 Power and man labor cost

Power and man labor costs have a great dependency on the EU28 countries as can be consulted in Eurostat Statistics [6] [7], especially the last one. Considering raw feedstock availability, the analysis on these factors allows to group countries as follows:

- Power cost (Table 2). Three groups can be distinguished: Italy (IT), Spain (ES), and Germany (GE) in the range of 94-90 €/Mwh, France (FR) and Romania (RO) about 83 €/MW·h, and Poland (PL) and Finland (FI) on an average of 70 €/MW·h.
- Estimated hourly labor costs (Figure 5) can fluctuate from more than 35 €/h to below 10 €/h: For France (FR), Sweden (SE), Germany (DE), and Finland (FI) labor costs are in the range of 37.5-34 €/h, while they amount to 30 €/h for Italy (IT), 22.5 €/h for Spain (ES), 11 €/h for Poland (PL), and 8 €/h for Romania (RO).

Table 2 Electricity prices for non-household consumers without tax in €/MWh [6]

Country	Cost (€/MWh)
Italy (IT)	93.9
Spain (ES)	93.1
Germany (DE)	90.8
France (FR)	83.9
Romania (RO)	82.4
Poland (PL)	73.1
Finland (FI)	66.9
Sweden (SE)	n.d.

n.d.: data not available

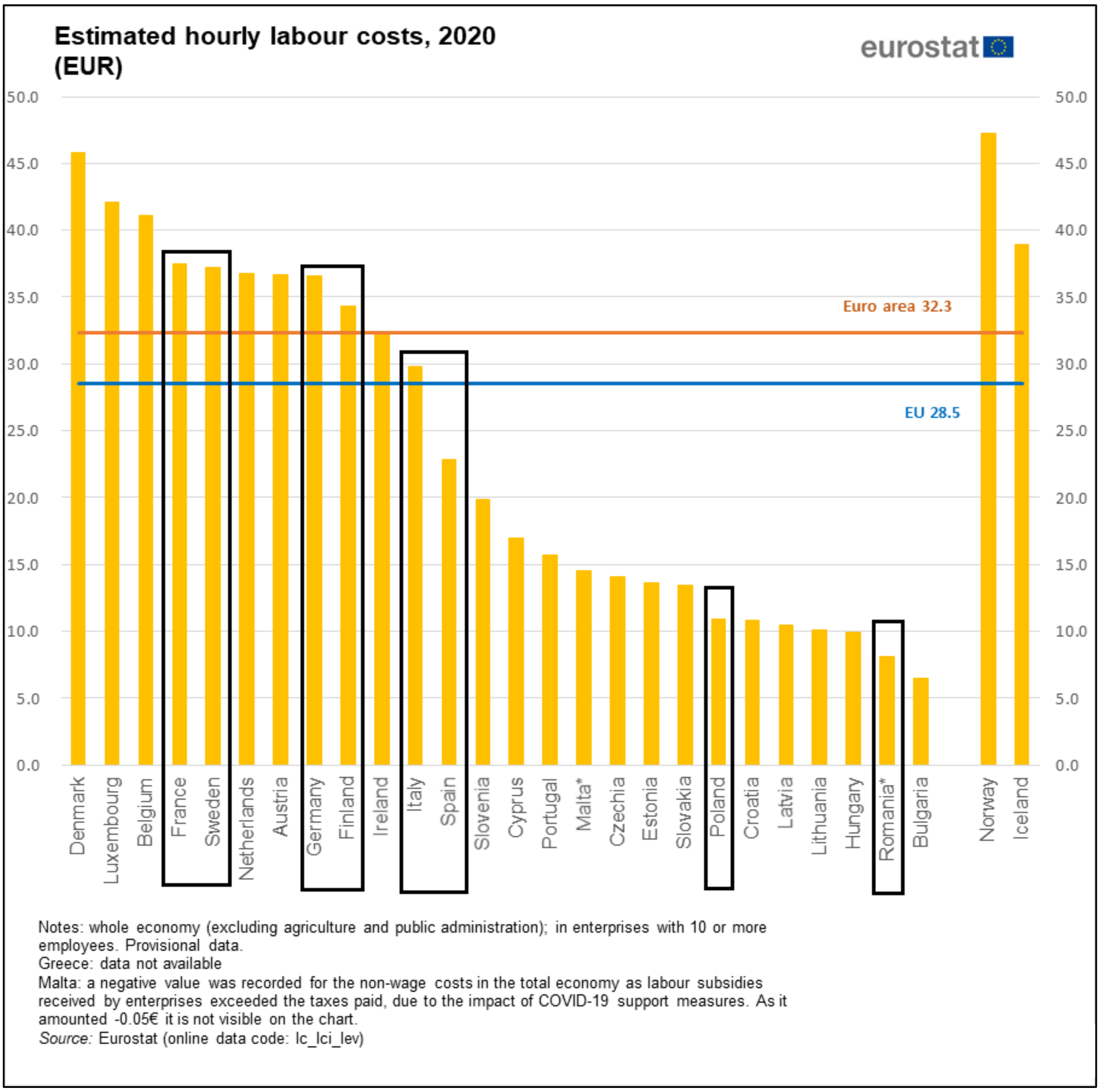

Figure 5 **Estimated hourly cost 2020** [7]

2.3 Grouping of base case scenarios

Based on the factors elaborated in Sections 0 and 2.2, three representative regions have been selected to calculate supply cost for the CLG plant. Values for each factor are detailed in Table 3:

- South Europe (SE): medium values for raw Feedstock prices, man labour cost and high for power.
- Central Europe (CE): medium values for raw Feedstock prices and power and high for man labour cost.
- East Europe (EE): low values for raw Feedstock prices, power and man labour cost.

Table 3 Raw Feedstock prices, power and man labour cost for base case scenarios

Region	Raw feedstock price (€/dry t)		Power cost (€/MW·h)	Man labour cost (€/h)
	WS	PFR		
South Europe (SE)	42.4	83.3	93.1	22.5
Central Europe (CE)	42.4	83.3	87.4	37.5
East Europe (EE)	30.0	65.0	72.0	11.0

The characteristics for both types of feedstock, wheat straw (WS) and pine forest residue (PFR), and the derived products (pellets) are the same in all cases (Table 4), in terms of energy content and chemical composition, except for the fact that for CE and EE scenarios a 20 % moisture content has been considered instead a 15 % for straw residues.

Table 4 Pre-treated pellets characteristics

Proximate analysis		Wheat Straw		Pine Forest Residue	
		Raw	Pellet	Raw	Pellet
Moisture content	wt.%; wb	15.0-20.0[(	10.0	40.0	9.5
Ash content	wt.%; db	7.5	9.3	2.0	2.0
Volatile matter	wt.%; db	77.7	77.7	73.2	73.2
Fixed carbon[(1)]	wt.%; db	14.8	13.0	24.8	24.8
Ultimate analysis					
C	wt.%; daf	49.6	49.6	52.7	52.7
H	wt.%; daf	6.2	6.2	6.4	6.4
N	wt.%; daf	0.42	0.42	0.39	0.39
S	wt.%; daf	0.113	0.113	0.05	0.05
Cl	wt.%; daf	0.108	0.108	0.008	0.008
O[(1)]	wt.%; daf	43.56	43.56	40.45	40.45
Net calorific value					
NCV	MJ/kg; daf	18.9	18.5	20.2	20.2

[(1)]value obtained by difference
wb: wet basis
db: dry basis
daf: dry and ash free basis
[(2)]15% for SE and 20% for CE and EE

3 Production Cost

3.1 CAPEX calculation

Capital expenditure (CAPEX) costs have been considered equal for all three base case scenarios and include investments for required equipment (see Table 5), considering plant size in kilotons per year (kt/y) and are expressed in euros. Depending on plant size, direct costs have been calculated according to the following equation:

$$Direct\ Cost_{X(\frac{ktn}{y})} = Direct\ Cost_{100(\frac{ktn}{y})} \left(\frac{X(\frac{ktn}{y})}{100(ktn/y)} \right)^{0.6} \tag{1}$$

Besides, the number of pelleting lines has been adjusted for each case to the plant size considering a production capacity of 5 t/h per line.

In addition to the detailed investments for equipment, the following investment concepts have been considered, for which, a percentage of the equipment investment cost have been considered: equipment installation (20%), pipes (30%), instrumentation and control (20%), power connections (10%), buildings (10%), and auxiliary facilities (5%).

Table 5 Equipment investment cost (Direct Cost)

Concept	Cost	Unit	Source
Chipping/Chopping	63,700	€	suppliers from CENER (APISA-MABRIK)
Drying	75,510	€	
Pelleting	962,780	€	

According to reviewed literature [8] [9], actual pellet mill plants can range from 10 kt/y up to nearly 300 kt/y production capacity. In the case of France (FR) or Germany (DE) a more detailed distribution and plant sized is reported by Thrän et al. [9] as is depicted in Figure 6.

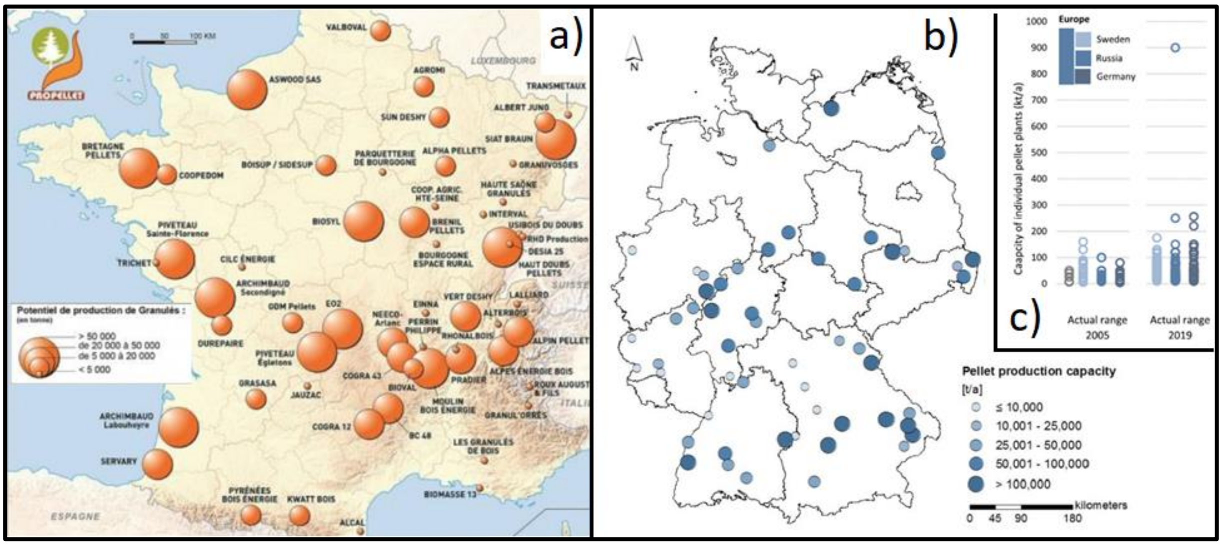

Figure 6 Production capacity and distribution of pellet mills in a) France, b) Germany [8] **and c) production capacity in Europe (Sweden, Germany and Russia)** [9]

Based on the available information, the calculated plant sizes ranged from 60 kt/y and 360 kt in the case of wheat straw residues, and up to 400 kt for pine forest residues. These figures are expressed as input raw material. In terms of production capacity, supply costs calculated for decentralized pre-treatment plants range from 55 kt/y up to 330 kt/y and from 35 kt/y up to 235 kt/y for wheat straw residues and pine forest residue, respectively. Note that for a CLG plant with a thermal load of 200 MW_{th}, operating 8,000 h/y, the required amount for each feedstock, considering the net calorific values of the respective pellets (see Table 4), is about 386 kt/y of straw pellets and 322 kt/y of forest residue pellets.

3.2 OPEX calculation

Operational expenditures (OPEX) include the cost of raw feedstock at pre-treatment plant gate, power supply, and man labor cost as described in section 2.3. Other auxiliaries and maintenance cost has been fixed depending on plant size: for each pelleting production line, a yearly cost of 65,000 € has been considered.

To calculate the total man power cost, the total staff has been dimensioned for each plant scale. To cover 3 daily shifts and 7 days/week in a 180 kt/y input raw material with 4 pellet production lines, 15 operators and 4 responsible of shift with 2 extra persons for administrative, management and marketing labors were considered (D1.4). Depending on plant size, the 2 extra persons for administrative, management, and marketing are kept fixed, while operators and responsible of shift are recalculated depending on the number of total pelleting lines.

3.3 Production Cost

The data indicated in Table 6 have been considered for the calculation of the production cost (LPC) at plant gate.

Table 6 Criteria for production cost calculation (LPC)

DATA	VALUE
Plant Availability (hours)	8,000
[1]Licenses	1%
[1]General Cost (management, maintenance, administrative)	2%
Installation Lifetime (years)	20
Estimated interest rate of the debt	2.5%
Estimated inflation	2.0%
Interest rate of the debt (minus inflation)	4.5%

[1]Percentage over CAPEX

For each case, scenario (SE, CE and EE), plant size, and feedstock (WS or PFR) the *Levelized Production Cost* (LPC) is calculated based on total exploitation expenses, annual capital cost, and annual production according to the following equation (2):

$$LPC = \frac{Total\ Explotation\ Expenses + Annual\ Capital\ Cost}{Annual\ Production} \tag{2}$$

On the other hand, the Annual Capital Cost is calculated by equation (3):

$$Annual\ Capital\ Cost = Total\ Investement \cdot \left[\frac{(1-i)^n \cdot i}{(1-i)^n - 1}\right] \tag{3}$$

where "*i*" is the estimated interest rate of debt in percentage divided by 100, and "*n*" is the installation lifetime in years

Pellets production cost as a function of product plant capacity are represented in Figure 7 for each base case scenario and feedstock. As expected, the higher the production capacity, the lower the production cost except at lower scales were the number of pellet production lines must be adjusted to run at nearly its maximum capacity (5 t/h).

In all cases, three ranges of production cost can be observed. Wheat straw shows production cost variations at the production capacities below 70 kt/y, from 120 kt/y to 170 kt/y and above 180 kt/y. The same effect is observed for forest residue pellets below 50 kt/y, from 70 kt/y to 100 kt/y and above 120 kt/y.

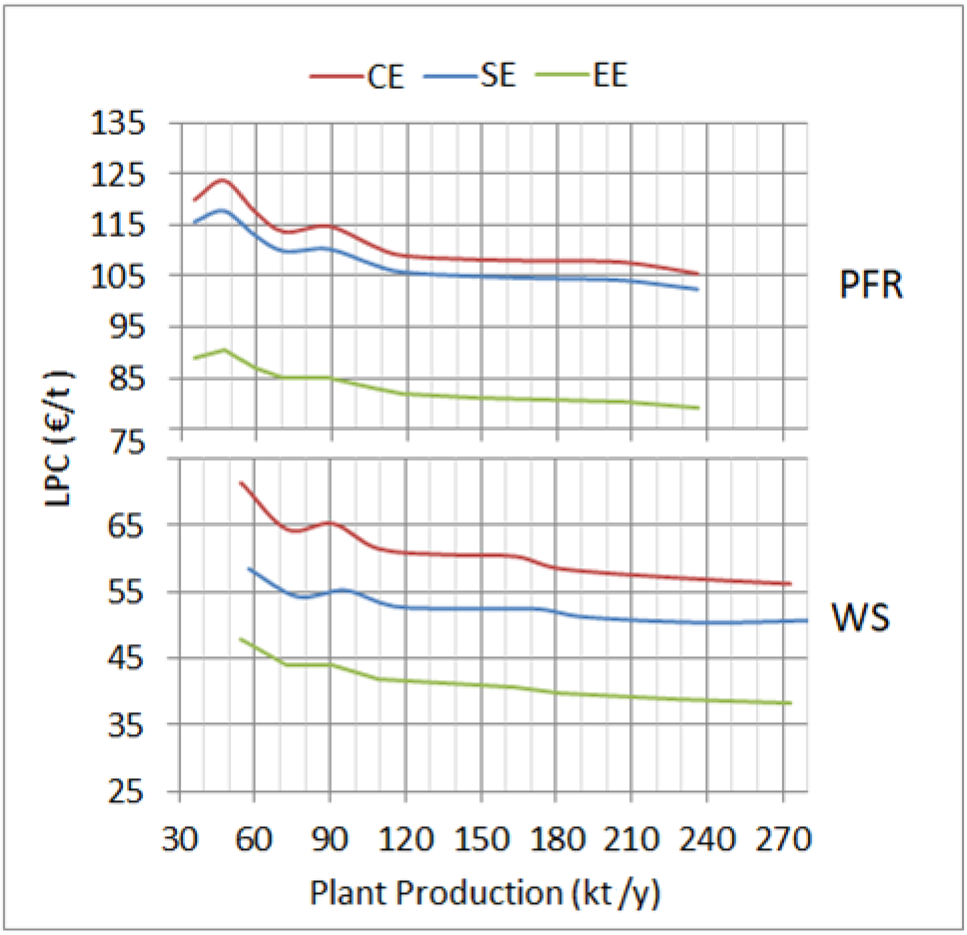

Figure 7 Production cost (€/t) for WS and PFR as a function of production capacity (kt/y)

A more detailed production cost (€/t) for four different production capacities is detailed in Table 7 for both biomasses on each base case scenario. For wheat straw pellets, differences in the final production cost greater than 13% can be observed mainly due to labour cost; 22.5 €/h and 37.5 €/h respectively and drying requirements, as the feedstock price is the same for SE and CE cases. These differences in the production cost are even larger when comparing both (SE and CE), 22% and 32% respectively, with the EE case, calculated with man labour cost of 11 €/h and feedstock price of 30 €/t (dry) instead of 42.4 €/t. Here, the difference in the feedstock price is 29%.

The same analysis for pine forest residue pellets shows only slight differences. Between SE and CE cases, the costs are 4% lower for the former, due to the greater impact of the feedstock cost, 83.3 €/t (dry) and the same drying requirements. The difference in feedstock price, (22% lower for the EE) explains the differences between the SE case (23%) and the CE case (25%).

Table 7 Production cost (€/t) depending on scale size for wheat straw residues (WS) and pine forest

residues (PFR)

Production Capacity (kt/y)	WS		
	SE	CE	EE
210	51.8	58.5	39.5
140	52.9	60.0	40.8
100	53.9	63.2	42.7
65	56.1	65.8	44.7

Production Capacity (kt/y)	PFR		
	SE	CE	EE
170	105.0	108.6	81.2
120	105.8	109.1	81.8
70	109.9	113.7	84.9
60	113.1	117.8	87.2

4 Supply Cost

4.1 De-centralized Configurations

In the next step, several possible configurations for the CLG pellets supply have been evaluated as depicted in **Fehler! Verweisquelle konnte nicht gefunden werden.** and detailed in Table 8, considering the real demand as 386 kt/y and 322 kt/y for straw pellets and forest residue pellets, respectively.

Fehler! Verweisquelle konnte nicht gefunden werden. represents, for wheat straw pellets (WS) and pine forest residue pellets (PFR), different supply scenarios for the CLG plant named as configurations. In each configuration (up to 6 configurations) different pellet production plant capacities in kt/y (Y axis) and pellet plant units (number of plants in X axis) are required to ensure the pellet supply to the CLG plant.

As mentioned, six different possible supply configurations (grouped by colors), combining pre-treatment plants with scale sizes from 65 kt/y up to 210 kt/y have been evaluated for straw pellets while for forest residue pellets the pre-treatment plants range from 60 kt/y up to 170 kt/y. The total number of plants range between 2 and 6. Besides, the total staff or direct employ generated by all the pre-treatment plants has been calculated for each possible configuration in order to evaluate social aspects in Section 5.

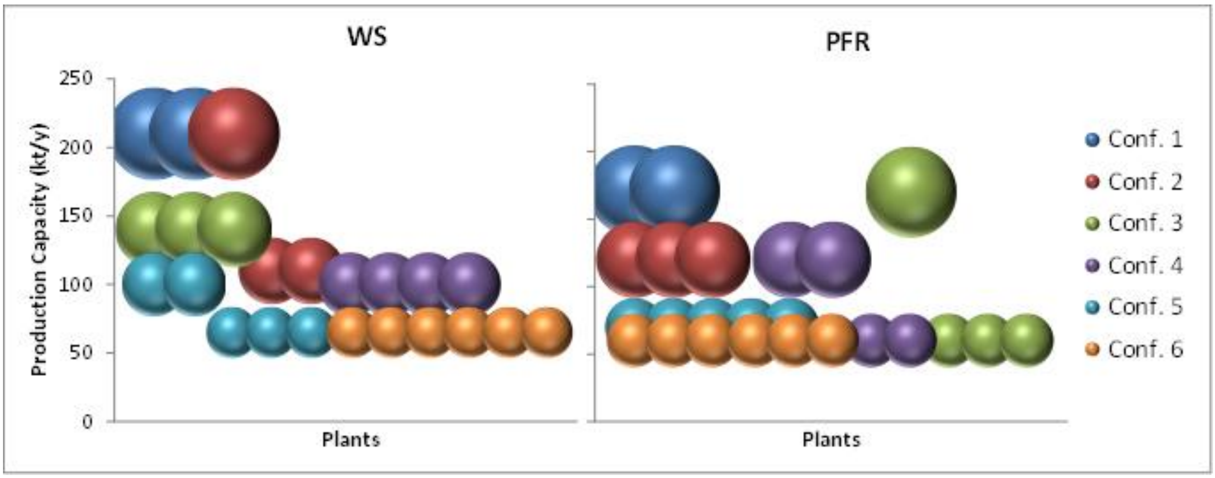

Figure 8 De-centralized configurations: number of pre-treatment plants and production capacity for wheat straw pellets (WS) and forest residue pellets (PFR)

The weighted average production cost (see Table 9) for each possible configuration, the average production cost for all configurations, and the relative standard deviation (RSD) allow having a more accurate range for production cost for each base case scenario and evaluate the cost variability. Considering RSD, from 2.6% to 4.6%, no drastic changes in production cost are expected derived from the possible configuration in terms of number of plants and respective production capacity for each base case scenario if the average production cost for the evaluated configurations is used as reference.

Table 8 De-centralized possible configurations

Configuration	WS Production Capacity (kt/y)	WS Number of Plants	WS Direct Employment (persons)	PFR Production capacity (kt/y)	PFR Number of Plants	PFR Direct Employment (persons)
1	210	2	62	170	2	52
2	210 100	1 2	65	120	3	51
3	140	3	63	170 60	1 3	62
4	110	4	68	120 60	2 2	58
5	100 65	2 3	70	70	5	60
6	65	6	72	60	6	72

Table 9 Weighted average supply cost (€/t) depending on configuration excluding transport and storage

Configuration	WS SE	WS CE	WS EE	PFR SE	PFR CE	PFR EE
1	51.8	58.5	39.5	105.0	108.6	81.2
2	52.8	60.8	41.1	105.8	109.1	81.8
3	52.9	60.0	40.8	109.1	113.2	84.2
4	53.9	63.2	42.7	108.2	112.0	83.6
5	55.0	64.5	43.7	109.9	113.7	84.9
6	56.1	65.8	44.7	113.1	117.8	87.2
Average	**53.7**	**62.1**	**42.1**	**108.5**	**114.4**	**83.8**
Minimum	51.8	58.5	39.5	105.0	108.6	81.2
Maximum	56.1	65.8	44.7	113.1	117.8	87.7
RSD (%)	**2.9**	**4.6**	**4.6**	**2.7**	**3.0**	**2.6**

To evaluate the impact on production cost of capital and operational costs, the production capacity has been set to obtain the average production cost from Table 9, to allow evaluating the contribution of each factor (Table 10 and Table 11). This analysis is done by the levelized production cost, which expresses the contribution (percentage) of each factor to the final cost.

Table 10 Breakdown for levelized production cost (%) for average calculated production cost excluding transport and storage with and without feedstock impact for wheat straw residues

Wheat Straw	SE		CE		EE	
Feedstock (%)	69	-	60	-	62	-
Maintenance & Repair (%)	3	11	3	7	4	11
Power and Drying (%)	12	38	15	37	19	49
Man Power (%)	12	39	17	43	7	20
Management & Administration (%)	1	3	1	3	2	5
Capital Cost (%)	3	9	4	9	5	14
LPC (€/t)	**53.7**		**62.1**		**42.1**	
Production capacity (kt/y)	**107.5**		**105.6**		**105.6**	

Due to the impact of the feedstock prices, the breakdown for levelized production cost in percentage terms is also detailed without the effect of feedstock cost. It can be stated that production cost for the pellets vary depending in feedstock prices by factor of 0.60-0.69 for wheat straw pellets and 0.75-0.79 for forest pellet residues.

Table 11 Breakdown for levelized production cost (%) for average calculated production cost excluding transport and storage with and without feedstock impact for pine forest residues

Pine Forest Residue	SE		CE		EE	
Feedstock (%)	78	-	75	-	79	-
Maintenance & Repair (%)	2	8	2	7	2	11
Power and Drying (%)	10	46	9	37	10	48
Man Power (%)	6	29	10	42	4	19
Management & Administration (%)	1	4	1	4	1	6
Capital Cost (%)	3	12	2	10	3	15
LPC (€/t)	**108.5**		**112.4**		**83.8**	
Production capacity (kt/y)	**98.5**		**99.1**		**98.5**	

4.2 Transport and Storage Cost

The final cost of the pellet supply, straw residue pellets or forest residue pellets, to the CLG plant should include transport and storage cost. Transport cost has been identified only for truck, not for rail or other media, since the value chain assume a central CLG plant supply by decentralized pre-treatment plants around the former.

The average transport cost for pellets considered by the last report of the International Energy Agency was estimated in 0.04-0.045 €/t km [9] in 2017. For a 200 km distance via truck the reported value including backhaul is about 20.8 €/t, which correspond to 0.104 €/t km similar to the cased of long term contracts in Sweden of 0.10 €/t km.

Nevertheless, the cost varies depending on distance [10], but from 80 km up to more than 200 km, the cost becomes more or less constant in terms of €/t km. Rogers et al. [10] reported a cost about 0.3 p/GJ km which correspond to 0.067-0.069 €/t km considering net calorific values (Table 4) and 1.2 factor for money exchange for pound to euro for wood chip transportation.

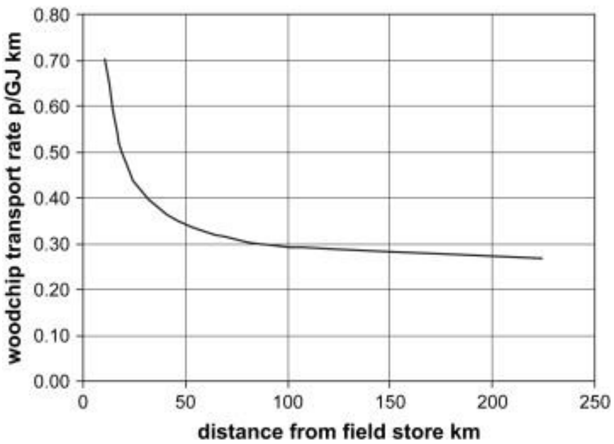

Figure 9 Transport rate needed to cover woodchip transport cost from different field stores

Since either wheat straw pellets or pine forest residue have the same bulk density (>600 kg/m^3), the transport cost has been considered equal as 0.10 €/t km.

In order to calculate the required transport distance on each base case scenario, several calculations have been done based on literature data. It should be taken into account that is being considering a CLG plant operating 8,000 h/y, with a fed necessity of 386 kt/y and 322 kt/y of straw pellets and forest residue pellets respectively (see Table 12), which corresponds to 355 kt/y and 292 kt/y of dry feedstock in each case.

Biomass generation for straw residues [1] and forest residues (stock above ground) [3] for three representative countries, such as Spain, Germany and Poland, corresponding to the three base case scenarios (SE, CE and EE respectively), allow for a calculation of the available biomass in terms of t/ha·y for each feedstock.

For cereal straws, a share of 61%, corresponding to the sum of wheat and barley from the total amount of cereal residues, has been applied [1]. On the other hand, for forest residues two considerations have been done: the stock above ground [3] is exploited in 10 year and according to estimations made by Hoefnagels et al. [11], the potential of forest residue generation has been set as 20% of forest biomass potential.

Finally, a security factor has been applied on each base case on share of arable land [12] and available forest area [13], since biomass available density and annual production capacity is neither homogeneous or stable among each considered region.

The supply of the CLG plant should not affect market price, therefore, a low share of the available feedstock must be consumed by the CLG plant. Shares from 4% up to 16% have been applied to the available biomass (t/ha·y dry), considering the calculated required transport distances. Based on the above mentioned calculations, an average transport distance is estimated, taking into account the radius needed to cover the area to satisfy the pellets demand of the CLG plant.

Table 12 **Annual Availability considered for straw and forest residues for base case scenarios**

Factor	Unit	SE (Spain)	CE (Germany)	EE (Poland)
Area	(km^2)	506,000	357,00	313,000
			Straw	
Generation	(Mt/y dry)	30	45	38
Share of Wheat and Barley	(%)		61	
Availability	(t/ha·y dry)	0.59	1.26	1.21
Share of arable area	(%)	49	47	46
[1]Transport cost	(€/t)	25.4	17.8	18.2
			Forest Residues	
Stock aboveground	(t/ha dry)	30	90	70
Availability	(t/ha·y fry)	0.60	1.80	1.40
Share of forest area	(%)	37	32	30
[1]Transport Cost	(€/t)	20.4	12.7	14.9

[1]Calculated for a 10% share of the available feedstock consumed by the CLG plan

Transport distance is greatly affected by biomass availability and the share consumed by the CLG plant; below 10% (see Figure 10). The transport cost considered has been set at the optimal transport distance for the each base case scenario:

- Straw residue pellets: 254 km (ES), 178 km (CE) and 182 km (EE).
- Forest residue pellets: 204 km (ES), 127 km (CE) and 149 km (EE).
-

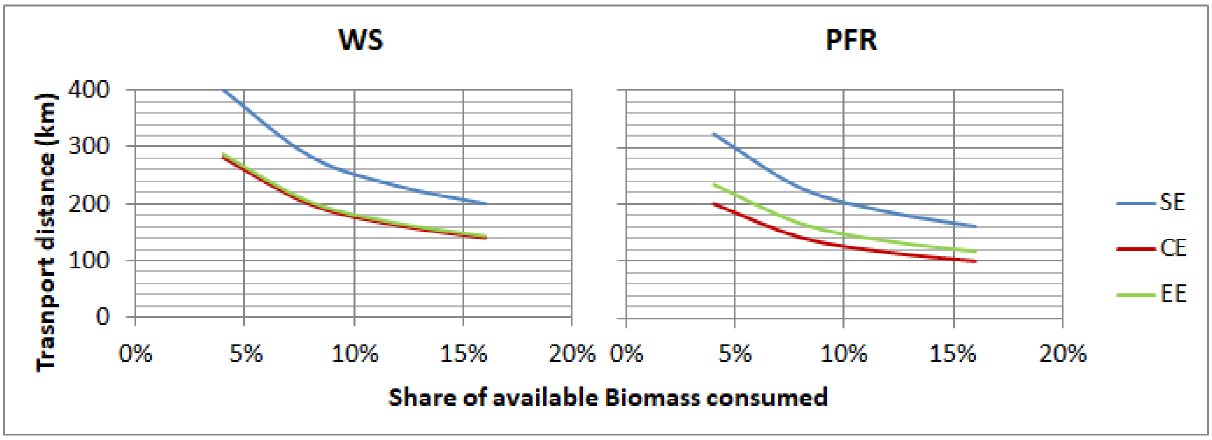

Figure 10 **Transport distance calculated for straw (WS) and forest residues (PFR) depending on share of available feedstock**

Despite the lower production cost in SE compared with CE, due to biomass availability and therefore required transport distance, prices become similar while in EE remain lower (Table 13).

In the present report, storage costs are referred to pellets, since storage cost of raw material is included in the corresponding feedstock price. It has been assumed that most of the plants, either pellet mills or thermal plants only have buffer storage capacity for a few days of storage [14]. Cost due to wheat straw availability along the year (2 month harvest window) has been included in the feedstock price.

Data used to calculate storage costs for pellets are available in literature [15], based on energy density, being the cost proportional to the basis of storage volume. In this sense, the study assumes that straw pellets have an energy density about 3.2 times higher than raw feedstock and storage costs of 0.10 €/GJ for 20 days, which correspond to 0.65 €/t·week.

Table 13 **Supply cost (€/t) for wheat straw residues (WS) and pine forest residues (PFR) including production cost and transport**

€/t	WS			PFR		
	SE	CE	EE	SE	CE	EE
Production	53.7	62.1	42.1	108.5	112.4	83.8
Transport	25.4	17.8	18.2	20.4	12.7	14.9
Total	**79.1**	**79.9**	**60.3**	**128.9**	**125.1**	**98.7**

The extra cost from storage must be added to the total pellets supply cost, but since, as mentioned, it is about 0.65 €/t·week for a storage period no longer than three weeks, it can be assumed that only 2 €/t are expected.

Considering pellet demand for the CLG plant is 48 t/h for straw pellets and 40 t/h for forest residue pellets a buffer of three weeks will require storage space for 24.3 kt and 20.3 kt respectively, which corresponds to 40,500 m^3 and 33,800 m^3 (pellets density 600 kg/m^3).

4.3 Pellet Cost Development

Raw material cost (feedstock price) can vary, impacting final pellet supply cost, since it is the main factor (see Table 10 and Table 11), due to annual variations in the productivity. The above mentioned price for feedstock [4] [5] can range from 29 €/t up to 50 €/t (dry t) in the case of straw residues and ranging 25-87 €/t for forest residues.

The effect of the feedstock price variation has been modeled by fixing the production capacities (Table 10 and Table 11) including transport cost calculated assuming a 10% share of the available feedstock supplies of the CLG plant (see Table 12). Results for the pellet supply cost including transport are plotted in merged format for both feedstocks and all base case scenarios in Figure 11. Modeled feedstock prices range from 25-50 €/t for wheat straw and 50-105 €/t for pine forest residues. Values plotted as squares represent production cost including transport calculated in the previous section (Table 13).

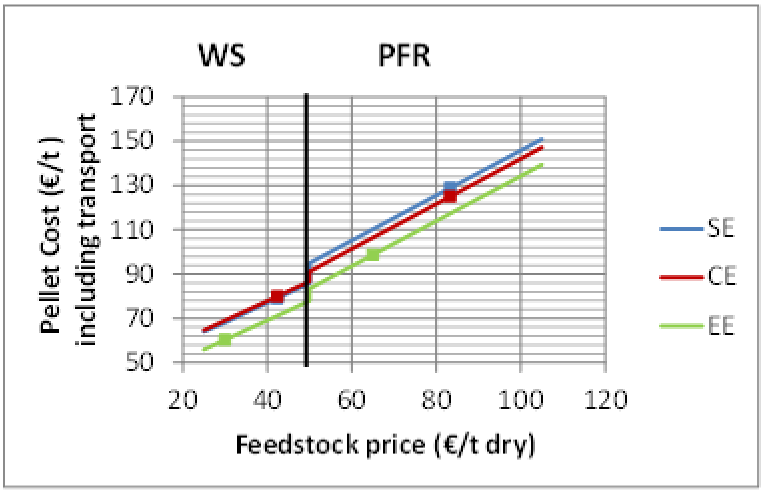

Figure 11 Pellet production cost (€/t) including transport for wheat straw (WS) and pine forest residues (PFR)

spite man labor cost or power cost, feedstock price is the main factor affecting the production and therefore supply cost for pellets (see Figure 12). See differences between continuous (wheat straw) and dotted (forest residue) lines in Figure 13: for the three considered base case scenarios as feedstock prices increase (same cost for both biomasses), the difference between supply cost for wheat straw pellets and forest residue pellets become larger.

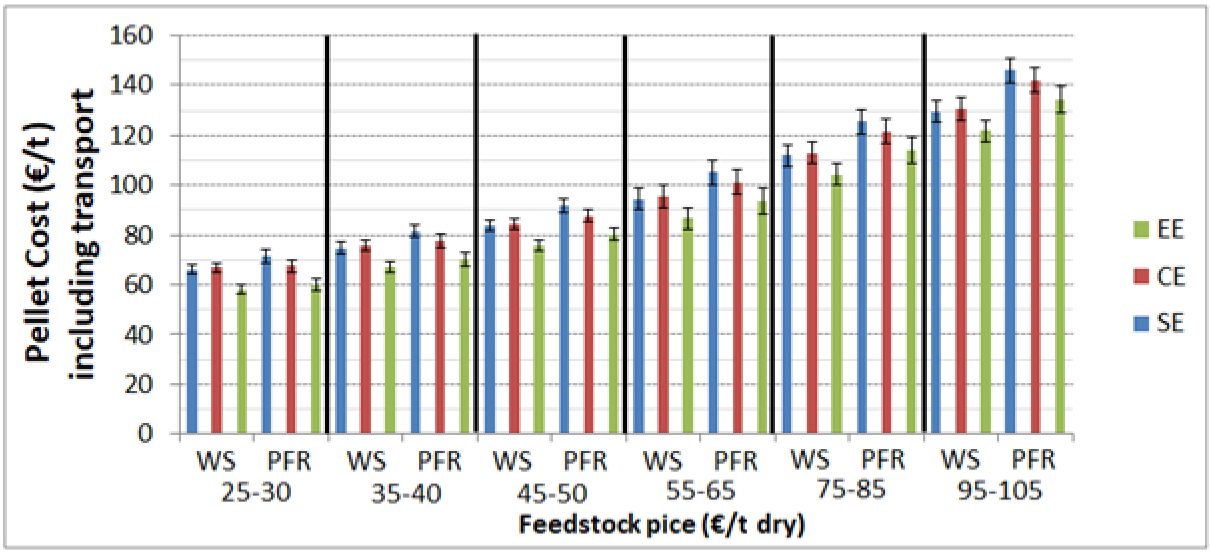

Figure 12 Grouped Pellet production cost (€/t) including transport for wheat straw (WS) and pine forest residues (PFR)

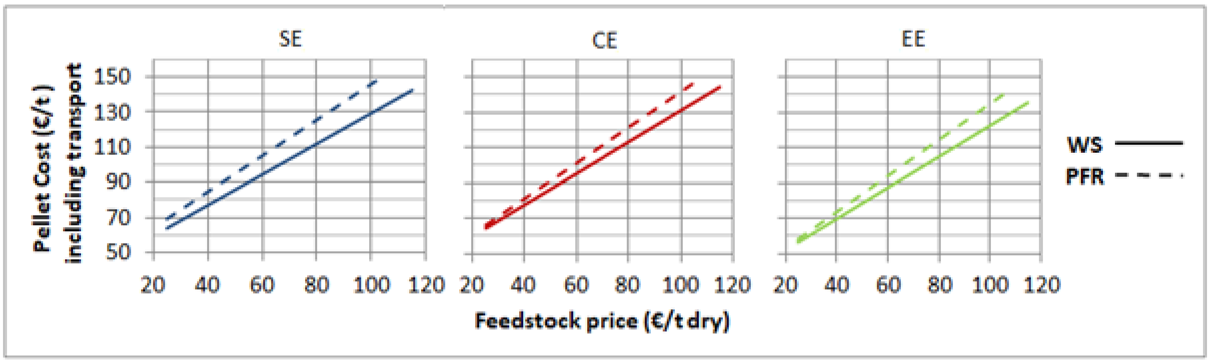

Figure 13 Split Pellet production cost (€/t) including transport for wheat straw (WS) and pine forest residues (PFR) for base case scenarios

Table 14 Supply cost (€/t and €/Mw·h) for wheat straw residues (WS) and pine forest residues (PFR)

	WS			PFR		
	Minimum	Average	Maximum	Minimum	Average	Maximum
€/t	**64.7**	**76.9**	**86.6**	**88.5**	**110.2**	**130.6**
€/Mw·h	**15.6**	**18.6**	**20.9**	**18.7**	**23.6**	**27.6**

In order to fix minimum, maximum, and most probable (average) supply cost for pellets, it has been considered that the feedstock price can range from 35 €/t up to 50 €/t (dry t) in the case of straw residues and from 55 to 85 €/t for forest residues. Considering these ranges for each feedstock price, the supply cost for pellets are detailed in Table 14 in both €/t and €/Mw·h. It should be taken into account that final pellet characteristics such as moisture content, ash content and net calorific value (see Table 4) have been considered for each case.

Finally, evolution of historical industrial pellets cost shown a great variability in the last ten years [16]: minimum prices were reached in January 2017 (110 $/t) and a maximum two years later with values of 210 $/t. Considering an actual ex-change of 1.1 $/€ this corresponds to 100 €/t and 190 €/t with typical values ranging 127-173 €/t.

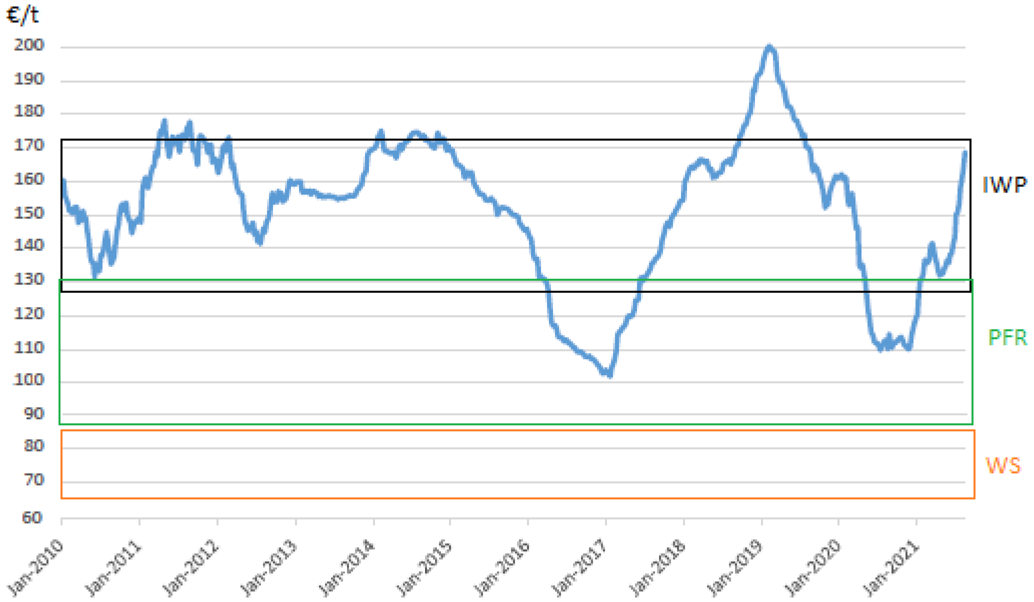

Figure 14 Evolution of historical industrial pellets (IWP) cost compared to calculated values for wheat straw pellet (WS) and pine forest residue pellets (PFR). Modified from [16]

5 Social aspects

The energy sector is responsible for more than 75% of greenhouse gas (GHG) emissions in the European Union (EU). Increasing the share of renewable energies among the different sectors of the economy is a key factor to reach an integrated energy system that achieves the climate neutrality that Europe seeks.

Bioenergy can play a key role in achieving the EU's renewable energy targets for 2030 and beyond. Agricultural and forestry biomass residues are a promising alternative to fossil fuels for producing electricity, heat and liquid fuels because it can be exploited renewably. CLARA project aims to produce a drop-in fuel from renewable sources such as biogenic residues to substitute fossil fuel, not competing with biomasses derived from the food chain and contributing to promotion and exploitation of rural areas. Therefore, CLARA technology can play an important and constructive role in achieving the agreed UN Sustainable Development Goals (SDGs) and implementing the Paris Agreement on Climate Change, thereby advancing climate goals, food security, better land use, and sustainable energy for all:

- SDG-13: take urgent action to combat climate change and its impacts. CLARA project contributes to lower GHG emissions in the value chain.
- SDG-7: ensure access to affordable, reliable, sustainable, and modern energy for all. This goal is achieved ensuring local energy as straw is a source that is mainly used locally.
- SDG-2: end hunger, achieve food security and improved nutrition, and promote sustainable agriculture. Since the feedstock that is being used in the project are non food competitive raw material.
- SDG-15: protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. Agricultural biomass supply chains (energy crops and residues) are most likely to contribute to SDGs 2 (Zero Hunger), while waste and forest supply chains are most likely to contribute to SDG 15 (Life on Land)

Therefore, it can be stated that CLARA project contributes in achieving both circular economy objectives and UN SDG.

In 2018, 19% of the energy consumed in Europe came from renewable sources and of that 58% comes from biomass. Almost 75% of the biomass energy consumed in Europe is for thermal uses [3], ahead of the electricity consumption (13.4%) and biofuel for transport (12%). Of all biomass used, only 4% is imported and 93% is locally consumed.

There are significant opportunities for developing the use of agro-forest residues and by-products, as well as waste. Moreover, biomass is a readily available local resource which will present local rural areas that grow it with an opportunity to diversify their agricultural output and sources of income.

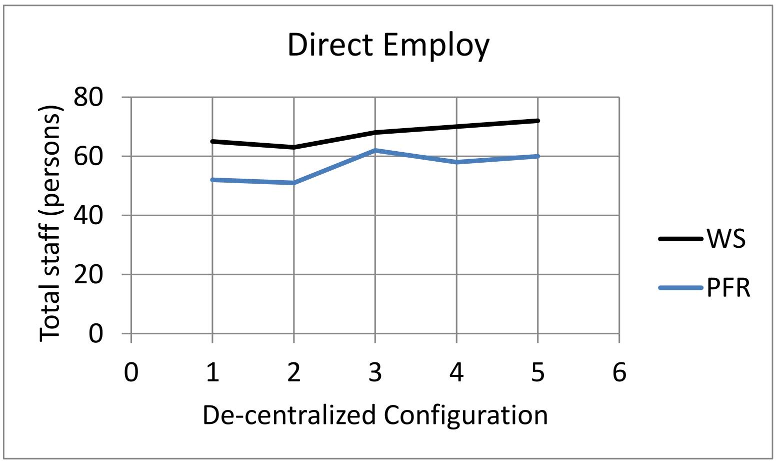

Figure 15 Total staff (direct employ) depending on de-centralized configuration

Rural areas have higher percentages in terms of unemployment and social poverty in the EU, compared to urban or intermediate areas [17], the main social benefit is the direct employment generation by the possible de-centralized configurations (Figure 15). Considering this parameter and the covered area for CLG demand supply (transport distance), the social impact can be expressed as the number of positions generated per square kilometer contributing to the percentage of holdings with other gainful activities. Results show average values for all possible configurations of 0.26-0.29 position/km^2 for SE, agro and forest residues respectively, 0.37 position/km^2 in CE and EE in the case of straw residues and 0.47 position/km^2 for SE and 0.40 position/km^2 for EE for forest residues.

6 Conclusions

Pellet production and supply cost are impacted in order of importance by the following factors: raw feedstock price, man labour cost, and power cost. Therefore, three representative regions have been selected to calculate wheat straw pellets and forest residue pellets production cost, depending on pre-treatment plants scale size. Besides, production cost also depends on production capacity of the pre-treatment plant. In this sense and independently from the location or the biomass cost three ranges of production cost can be observed from calculations in section 3.3 (see Figure 7)

Up to six possible supply configurations, combining scale sizes from 65 kt/y up to 210 kt/y, have been evaluated for straw pellets and pre-treatment plants with outputs from 60 kt/y up to 170 kt/y for forest residue pellets. Despite the different scale size and total number of plants (2-6), no drastic changes in production cost are expected for the possible configurations.

The required transport distance for the pellet supply is greatly affected by availability of the biomass and the share of this available biomass consumed by the CLG plant. The effect of share of available biomass consume by the CLG plant on the required transport distance has been calculated. Results shown that a 10% share of biomass consumed by the CLG plant can be considered the optimal (see change in slopes in Figure 10). Due to biomass availability and despite the lower production cost in SE compared with CE, supply cost become similar while in EE base case scenario costs remain lower.

Table 15 Summary for base case scenarios for wheat straw pellets (WS) and pine forest residues pellets (PFR)

Parameter	Units	WS			PFR		
		SE	CE	EE	SE	CE	EE
Average Production Cost	(€/t)	53.7	62.1	42.1	108.5	112.4	83.8
Minimum Production Cost	(€/t)	51.8	58.5	39.5	105.0	108.6	81.2
Maximum Production Cost	(€/t)	56.1	65.8	44.7	113.1	117.8	87.7
[1]Transport distance	(km)	254	178	182	204	127	149

[1]Transport cost 0.1 €/t·km

Pellet supply cost is greatly affected by feedstock price variability ranging for straw residues from 35 €/t up to 50 €/t (dry t) and from 55-85 €/t for forest residues. Therefore, supply cost for pellets can range as follows:

- Wheat straw pellets from 64.7-86.6 €/t with estimated average values of 76.9 €/t
- Pine forest residue pellets from 88.5-130.6 €/t with estimated average values of 110.2 €/t

Differences between agro or forest residue pellets become narrower if the net calorific value is considered but in any case are competitive when compared with the evolution of spot prices for industrial wood pellets which typically cost between 127 €/t and 173 €/t in the last 10 years.

De-centralized pre-treatment plants can contribute directly or indirectly to achieve EU's renewable energy targets for 2030 and several of the agreed UN Sustainable Development Goals (SDGs 13, 7, 2 and 15). Besides, the use of available local resources in rural areas is an opportunity to diversify their agricultural output and sources of income, thus contributing to reducing differences with urban or intermediate areas in terms of unemployment and social poverty.

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