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Optimization and Investment Analysis of two Biomass-to-Heat Supply Chain Structures

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Abstract
As oil prices have risen dramatically lately, many people explore alternative ways of heating their residences and businesses in order to reduce the respective cost. One of the options usually considered nowadays is biomass, especially in rural areas with significant local biomass availability. This work focuses on comparing two different biomass energy exploitation systems, aiming to provide heat at a specific number of customers at a specific cost. The first system explored is producing pellets from biomass and distributing them to the final customers for use in domestic pellet boilers. The second option is building a centralized co-generation (CHP) unit that will generate electricity and heat. Electricity will be fed to the grid, whereas heat will be distributed to the customers via a district heating network. The biomass source examined is agricultural residues and the model is applied to a case study region in Greece. The analysis is performed from the viewpoint of the potential investor. Several design characteristics of both systems are optimized. In both cases the whole biomass-to-energy supply chain is modeled, both upstream and downstream of the pelleting/CHP units. The results of the case study show that both options have positive financial yield, with the pelleting plant having higher yield. However, the sensitivity analysis reveals that the pelleting plant yield is much more sensitive than that of the CHP plant, therefore constituting a riskier investment. The model presented may be used as a decision support system for potential investors willing to engage in the biomass energy field.

Keywords: Optimization, Pelleting, Co-generation, Biomass, Investment analysis.

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Sets and Indices		Description
i	$i=1...n$	Biomass type
l	$l=1...L$	Distance class from pelleting/power plant
t	$t=1...T$	Time period (months)
Variables	**Units**	**Description**
$B_{i,l}$	t wet biom.	Annual amount of the ith biomass type to be procured from distance class l
Ppl	t h^{-1}	Capacity of pelleting plant
$Qpel_0$	t	Initial annual pellet inventory
V_0	m^3	Initial annual biomass inventory
Xp & Yp	km	Longitude & Latitude of pelleting plant (geographical coordinates)
Parameters	**Units**	**Description**
A	kg$_b$ kg$_{pel}^{-1}$	Quantity of wet biomass required to produce 1 kg of pellets (mean)
Cb_i	€ t^{-1}	Purchasing and loading cost of wet biomass of type i
Cpel	€ kg^{-1}	Selling price of pellets
Ctd_i	€ km^{-1} t^{-1}	Distance-specific transportation cost of biomass type i
Ctdp	€ km^{-1} t^{-1}	Distance-specific transportation cost of pellets
Ctt_i	€ h^{-1} t^{-1}	Time-specific transportation cost of biomass type i
Cttp	€ h^{-1} t^{-1}	Time-specific transportation cost of pellets
Cup	€ t^{-1} h	Specific investment cost of pelleting plant
d	-	Tortuosity factor (real travel distance/Euclidean distance)
Dbm	kg m^{-3}	Mean biomass density
Df	-	Discounting coefficient
D_l	km	Biomass transportation trip distance for distance class l
Iwb	€	Biomass warehousing and related equipment investment cost
Iwpel	€	Pellets warehousing and related equipment investment cost
Hdry	kWh t^{-1}	Heat required to dry 1 ton of pellets
Hm	kJ kg^{-1}	Mean lower heating value of annual biomass mix
Hupel	kJ kg^{-1}	Mean lower heating value of pellets
Ls	km	Safety distance from pellet consumers
N	years	Investment lifetime
OMpl/wb/wpel	€ year^{-1}	Operational &Maintenance cost for (pl) Pelleting plant / (wb) Biomass warehousing / (wpel) Pellets warehousing
$Qpel_{t,l}$	t	Quantity of pellets produced during period t and dispatched to customers in distance class l
r	%	Interest rate
$Rinv_{10}$ / $Rinv_{15}$	%	Percentage of initial investment required to reinvest during years 10 and 15
T_l	h	return trip time for transporting biomass from distance class l
Tp_l	h	return trip time for distributing pellets to distance class l
Twhm	h month^{-1}	Operational time of pelleting plant within one month
V_t	m^3	Biomass inventory in period t
Xb_l / Yb_l	km	Longitude / Latitude of biomass fields or customers in distance class l
Xd / Yd	km	Longitude / Latitude of pellet consumers
ρ	%	Inflation rate

Table 1. Notations

1. Introduction

Biomass is a renewable energy source that has been used by mankind since ancient years. Lately, biomass has gained significant attention, due to the necessity of reducing CO_2 emissions and the technological improvements in biomass energy conversion. In addition, biomass use has been favoured by the recent increase in oil prices, leading many people to

explore alternative means of heating their residences and businesses in order to reduce the respective cost.

Several biomass types currently have alternative use (for example in the paper and pulp industry, as animal feedstock and bedding etc.), whereas others do not. Usually agricultural residue biomass types belong to the second category. In many cases, agricultural residue biomass is either not exploited or in some cases is burned in the fields, as it can be hazardous for cultivations if left to decay. Tree prunings are one example, which is also used in this work. Prunings is a woody type of biomass, which means it is suitable for use in most types of biomass processing and energy conversion equipment. Furthermore, the fact that it does not currently have significant alternative use means that it may be procured at lower prices than commercial biomass types.

There exist various systems for generating energy from biomass. Lately, pellets from biomass have been extensively used worldwide (USDA, 2009). In Greece, pellets have also started being produced and are currently used in small quantities, but with a high rate of increase (Karkania et al., 2012). Pellets are a densified form of biomass with very low moisture, increased energy content, easy to handle, store and transport and have the advantage that their specifications can be standardised. For these reasons, using pellets for heating has seen dramatic increase over the last years.

Another option for biomass energy generation that has found many applications, particularly in northern Europe, is the centralised Combined Heat and Power (CHP) generation. This option has the advantage that biomass may be used to produce simultaneously electricity and heat. Electricity can be sold to the grid, usually at a premium price, due to the renewable nature of biomass, and heat can be used for industrial, commercial or domestic heating. However, transferring the heat to the final consumers usually entails investing in a district heating pipeline and distribution network.

The two abovementioned options can be used to address the heating needs of the same consumers. However, the respective supply chains have significant differences. The main difference among the two options is that in the pellets case, the production is disengaged from the demand, since pellets can be stored. In the CHP case heat has to be generated when demanded, as it cannot be stored in significant quantities and for a long time period.

The primary purpose of this work is to examine comparatively the two different above mentioned energy supply chain options, for addressing the same heating needs, in regions with significant availability of currently unutilised agricultural biomass sources. The comparison is performed from the scope of a potential investor willing to engage in the business of renewable energy generation. The question of finding the most appealing investment from the two options while satisfying the same heating needs with the same cost for the customers is to be answered here.

The significance of this work lies in the fact that a comparison of the two options has not been performed in the relevant literature, despite the fact that each of these energy generation options has been studied in isolation. In addition, a detailed optimization model of the pellet supply chain is presented, including the pellet distribution function. This may be considered a novelty, as in the relevant literature only simulation models or cost estimations can be found for the complete pellet supply chain.

2. Literature review

2.1 Biomass energy recovery and biomass supply chain

Energy recovery from biomass has been extensively researched in past (Mitchell et al., 1995) and in more recent studies (Rentizelas et al., 2010). The issue of biomass energy recovery is closely linked to biomass supply chain modeling. Various models concerning the supply chain of biomass have been published. The case of biomass-fired plants, producing combined heat and power (CHP) has been researched in Tatsiopoulos and Tolis (2003), whilst the case of energy tri-generation has been investigated in the study of Rentizelas et al. (2010). Moreover, CHP projects, realized in agricultural areas, have revealed the potential benefit of decentralized bioenergy generation (Pantaleo et al. 2009). Several authors have included the bioenergy conversion facility modeling in their supply chain models, generating electricity and/or heat. The results from using two biomass-to-electricity conversion technologies were compared in Caputo et al. (2005), concluding that 56–76% of the total system operational costs are due to the biomass logistics, thus indicating the potential for cost reduction.

The concept of the exploitation of multiple biomass feedstocks has recently emerged, providing interesting alternatives to conventional single-biomass sourcing strategies (Rentizelas et al. 2009a, Rentizelas et al. 2009b). Apart from the logistical analysis, the aforementioned studies investigated the need for optimizing the entire supply chain and the location of bioenergy facilities, using complex optimization algorithms. A linear programming (LP) optimization model has been presented (Cundiff et al., 1997) to optimize a cost function including the biomass logistics activities between the on-farm storage locations and the centrally located power plant, construction and expansion costs of storage facilities, as well as the cost of violating storage capacity or lost revenue in case of biomass deficit. A GIS-based model to estimate the potential for electricity production from multiple agricultural residues was developed in Voivontas et al. (2001). In a similar vein, a techno-economic assessment of a biomass power plant was performed in Papadopoulos and Katsigiannis (2002), using a mixture of several biomass types. The authors focused mainly on reducing the biomass logistics costs and more specifically on eliminating biomass warehousing needs by performing a two-stage optimization: firstly, the CHP power plant location was determined to minimize the transportation distance and secondly, dynamic programming optimization was employed to identify the optimum biomass fuel mix. Finally, a combination of GIS, mathematical modelling and optimization for energy supply at a regional level from forest biomass was presented in Freppaz et al. (2004).

2.2 Pellet production

Pellet production is an interesting option for potential investors. In general, pellet is competitive to biomass as far as energy recovery is concerned. However, the production and supply chain costs are different. The economics of pellet production have been examined in several recent studies. In the work of Sultana et al. (2010) a thorough analysis was performed, the cost structure was split in discrete components and the cost break-down was analyzed for different agricultural biomass pellet types and plant capacities. Mani et al. (2006) focused on wood pellets but also investigated the feasibility of alternative fuels for drying the wet biomass before the pelleting process. Thek and Obernberger (2004) carried out a detailed study of sawdust pellet production in a European plant. Urbanowski (2005) estimated the capital cost from the previous study and used it in designing a pellet plant in Canada. Hoque et al. (2006) estimated the economics of wood pellet production for export market. Finally, Pastre (2002) presented a cost analysis as well as the technical difficulties of pellet production from agricultural residue biomass, providing comparative data with wood pellets. Wood pellets are produced commercially around the world (USDA, 2009) but there is currently limited production of agricultural biomass pellets.

In general, pellets are a more efficient fuel source compared to raw biomass, due to their physical and chemical properties (Carrol and Finnan, 2012). Pellets may also be used for handling the by-products of other biofuels, like ethanol, as analyzed in the study of Tumuluru et al. (2010). The effect of process variables like die temperature and feed moisture content on the pellet properties (pellet moisture content, durability and pellet density) was explored in this study using a single pelleting machine.

3. Model

This work aims to compare two biomass-to-energy supply chains. In order to perform this comparison, the supply chain structures are optimized. The first supply chain concerns collecting biomass to produce pellets, which are then distributed to consumers for domestic heat generation. The second supply chain concerns using the same biomass sources in a co-generation unit to generate electricity and heat. Electricity will be fed to the grid, whereas heat will be distributed via a district heating network for residential use. To have a common basis of comparison, both systems are designed to be demand-driven, meaning that their target is to supply heat to the same number of final customers. The systems are optimized in financial yield terms from the viewpoint of a potential investor. The optimization criterion is the maximization of the Profitability Index of the investment, which has been chosen to remove the obstacle of the significantly different investment cost required for the two cases.

An effort has been made to use boundaries for the systems examined as similar as possible. This means that the biomass logistics are included in the study for both systems, from the point of loading biomass to the transportation vehicles and downstream. In-field agricultural operations are not included in the model. As far as the supply chain downstream of the pelleting/CHP plant is concerned, in the case of pellets the investor is assumed to provide and distribute the final product (pellets) to the consumers' door, whereas in the case of CHP the system included in the cost analysis extends up to the final customers' metering point. The model allows the use of multiple fuel sources. In both cases the use of agricultural biomass residues in the form of various tree prunings has been considered, due to the fact that this type of biomass seldom finds an alternative use and that it is a wood biomass, which is compatible with the existing pelleting and CHP technologies available.

In the case of the pelleting plant, its monthly production is determined by the minimum between a) the hourly capacity of the plant multiplied by the operational hours per month (equal to 600 hours) and b) the amount of raw biomass available in the warehouse. The CHP plant generates exactly the appropriate amount of heat required each month. It should be noted the CHP plant consists of a main base-load co-generation unit and a boiler used to cover the peak-load heat demand.

The multi-fuel concept is adapted from the multi-biomass model of Rentizelas et al. (2009a). The model presented in Rentizelas et al. (2009a) has been adapted and used for the case of the CHP plant. The model used for the pelleting case is analysed in detail below. The optimization method applied in both models is a hybrid optimization method presented in Rentizelas et al. (2010).

3.1 Objective Function.
The objective function to be maximized is the Profitability Index (PI) of the investment for the project's lifetime, before taxes. All the necessary elements of the system are included in the investment analysis, i.e. the pelleting plant, the supply chain of biomass and the supply

chain of pellets (distribution). In the CHP model case the CHP plant, the district heating network with the connection to the customers and the electricity transmission line and connection to the grid are also included. All operational costs are taken into account. The function to be maximized for the pelleting plant is:

$$MaxPI = \frac{PV_{income} - PV_{O\&M}}{PV_{investment}} \tag{1}$$

Where

$$PV_{income} = \left[1000 \cdot Cpel \sum_t Qpel_t \right] Df \tag{2}$$

$$PV_{O\&M} = \left[\sum_i \sum_l B_{i,l} Cb_i + \sum_i \sum_l B_{i,l} (Ctd_i D_l + Ctt_i T_l) + \sum_t \sum_l Qpel_{t,l} (CtdpD_l + CttpTp_l) + OMpl + OMwb + OMwpel \right] Df \tag{3}$$

$$PV_{investment} = Ppl \cdot Cup \cdot (1 + Rinv_{10}(\frac{1+\rho}{1+r})^{10} + Rinv_{15}(\frac{1+\rho}{1+r})^{15}) + Iwb + Iwpel \tag{4}$$

$$D_l = \sqrt{d \cdot [(Xp - Xb_l)^2 + (Yp - Yb_l)^2]} \quad \forall l \tag{5}$$

$$B_i = \sum_{l=1}^{L} B_{il}, \quad \forall i \tag{6}$$

Equation (2) refers to the Present Value (PV) of the revenue stream of the investment, which is pellet sales. Equation (3) refers to the PV of the operational and maintenance costs and equation (4) to the PV of investment and future reinvestment costs. It should be noted that the investment lifetime has been assumed to be 20 years in both cases to perform a fair comparison. Due to the fact that some categories of equipment of the pelleting plant have an expected lifetime of 10 or 15 years (Mani et al., 2006), a reinvestment has been included in the total investment cost. The reinvestment for the 15-year lifetime equipment has been only proportionally considered for the remaining operational life of the pelleting plant. All the annual monetary amounts are multiplied by an appropriate discounting coefficient Df, which turns them into present values, assuming that the annual amounts will be increased by the inflation rate ρ that will remain fixed for the investment's lifetime:

$$Df = \frac{1 - [1 + \frac{(r - \rho)}{(1 + \rho)}]^{-N}}{r - \rho} \tag{7}$$

3.2 Optimization Variables.
The optimization problem variables are the following:
- Xp & Yp: The optimum location (geographical coordinates) of the facility.
- Ppl: The capacity of the pelleting plant.
- B_i: The total amount of the ith biomass type to be procured each year.
- V_0: The initial annual biomass inventory.
- $Qpel_0$: The initial annual pellet inventory.

The last two variables are necessary, as the calculations are based on a rolling yearly horizon framework, in the same vein to Cundiff et al. (1997).

3.3. Constraints.

Various constraints have been introduced in the mathematical formulation of the problem. The first constraint requires that there should be enough biomass collected to produce the pellets corresponding to the annual heat demand of the customers, plus the extra amount of biomass required as a fuel source to perform the drying process during pelleting. Mani et al. (2006) have examined the effect of various fuel options for the drying process and concluded that the most cost-efficient method is to use wet biomass, which is in line with the assumption made here:

$$\text{Hm} \cdot \text{Dbm} \cdot \sum_t V_t \geq (1000 \text{Hupel} + 3600 \text{Hdry}) \sum_t \text{Qpel}_t \qquad (8)$$

Additionally, there should always be a biomass safety stock in the warehouse to allow full capacity pellet production for a certain time period, here assumed to be equal to one fourth of a month, to allow the pelleting plant to continue operation in the event of a temporary biomass logistics disruption, e.g. because of extreme weather conditions:

$$V_t \cdot \text{Dbm} \geq 0,25 \cdot 1000 \cdot \text{Ppl} \cdot \text{Twhm} \cdot A \quad \forall t \qquad (9)$$

The warehousing space required for biomass (in both cases) and for pellets (in the pelleting case) is determined by the maximum monthly inventory divided by the stockpiling height (assumed 6m for biomass and 3m for pellets), allowing an extra 10% free warehouse space for moving the inventory. The warehouse is assumed to be a low cost solution of a pole-frame structure with a metal roof. However, in the CHP plant case, a certain amount of biomass should be kept in a more sophisticated closed warehouse with drying infrastructure using dumped heat from the plant, to reduce biomass moisture to acceptable levels before energy generation (Rentizelas et al., 2009b).

Two more constraints are introduced, due to the rolling horizon of the model: The finishing season biomass stock (V_T) must be at least as much as the starting season stock (V_0). The same applies for the pellets stock:

$$V_T \geq V_0 \qquad (10)$$

$$\text{Qpel}_T \geq \text{Qpel}_0 \qquad (11)$$

Due to the fact that industrial activity is not usually desirable in inhabited areas, a constraint has been added that the pelleting plant should be located at least at a safety distance (Ls) away from the customers' location (Xd, Yd), to avoid potential local opposition:

$$\sqrt{(Xp - Xd)^2 + (Yp - Yd)^2} \geq \text{Ls} \qquad (12)$$

Finally, all the independent variables are required to be non-negative and upper bounds are also defined for many of them. For example, the annual amount of biomass used is bounded by the maximum available quantity of this type (maxB_{il}) in the distance class l under examination:

$$0 \leq B_{il} \leq \max B_{il} \quad \forall i, l \qquad (13)$$

4. Case study

The application of the model has been performed for the case study municipality of Ampelonas, Greece. This municipality is located in the plain of Thessaly, where several

types of agricultural residue biomass are locally available. In this work, only tree prunings have been considered as raw material for pellet production or CHP generation (Table 2), despite the fact that they are not the dominant cultivations in the region. These biomass sources are characterised by seasonality, arising from time restrictions due to the primary product agricultural operations. The district energy customer will be the local community of Ampelonas of about 1900 households, from which about 1000 households have been assumed to be willing to receive either heat from the CHP plant or pellets from the pelleting plant. The investor could either be a private entity or a regional authority, and no subsidies of any kind have been included in the case study.

	1. Olive tree prunings	2. Almond tree prunings	3. Apple tree prunings	4. Peach tree prunings	5. Pear tree prunings	6. Cherry tree prunings
Biomass yield (t ha^{-1})[a]	2,54	5,59	4,29	5,05	15,23	4,60
Density wet biomass (kg m^{-3})	300	300	300	300	300	300
Moisture wet (%)[a]	35	40	40	40	40	40
Lower Heating Value (MJ kg$_{wet}$$^{-1}$)[a]	13,018	12,845	12,377	13,625	12,536	13,391
Availability period	Nov-Feb	Dec-Feb	Dec-Feb	Feb-Apr	Dec-Feb	Dec-Feb
Residue price (€ t$_{wet}$$^{-1}$)[b]	60	60	60	60	60	60

[a]Source: Voivontas et al. (2001), including assumption of 90% biomass availability for biomass yield
[b]Biomass price includes purchasing and loading cost, prices assumed equal to those of forest wood biomass.
Table 2: Characteristics of biomass types used

The revenue sources of the CHP facility under consideration are electricity sales to the national grid and heat supply to the customers via a district heating network. The electricity will be supplied directly to the national grid, at prices fixed by a long-term contract, due to the renewable nature of the electricity generated. The pelleting plant will only receive income from pellet sales. The price of heat sold by the CHP plant has been calculated based on the lower end of commercial pellet price in the region, assuming that domestic pellet boilers will have an average efficiency of 90%. Therefore, the real heating cost will be the same for the final consumers in either case. Most of the agricultural biomass types included in the study have no current alternative use; it is thus assumed that they may be procured at prices similar to those of forest wood biomass. Some of the most important parameter values used for the case study are presented in Table 3.

	Pelleting plant	CHP plant
Interest rate (%)	10	
Inflation (%)	2	
Electricity selling price (€ MWh^{-1})	-	201,25
Pellet selling price (€ t^{-1})	280	
Oil price (€ kg^{-1})	1,40	
Electricity price for pelleting plant/district heating (€ kWh^{-1})	0,15	
Investment lifetime (yr)	20	
Electrical efficiency of CHP unit (%)	-	29
Total efficiency of CHP unit (%)	-	85
Thermal efficiency of domestic pellet boiler (%)[e]	90	-
Pellet lower heating value (kWh kg^{-1})	5,3	
Pellet density (kg m^{-3})	600	

	Max 7200	When heat is demanded
Operational time (h yr^{-1})		
Investment cost of reference plant (€ t^{-1} h)/(€ kW$_{el}$$^{-1}$)	308000[d]	2000
Capacity of reference plant (t h^{-1})/(kW$_{el}$)	6[d]	2000
Scaling factor	0,75[a]	0,7
O&M of CHP unit (% inv.cost yr^{-1})	-	7
O&M of biomass boiler (% inv.cost yr^{-1})	-	3
Maintenance of pelleting plant (% inv.cost yr^{-1})[b]	2,8	-
Personnel cost of pelleting plant (€ t$_{pellets}$$^{-1}$)[c]	12,43	-
Investment cost of pelleting for Building, Packing & Misc. (€ t$_{pellets}$$^{-1}$)[c]	1,19	-
O&M of pelleting for Building, Packing & Misc. including bag consumables (€ t$_{pellets}$$^{-1}$)[c,d]	7,55	-

[a]Weighted average for all equipment from Sultana et al. (2010)
[b]Weighted average for all equipment from Mani et al. (2006)
[c]Source: Mani et al. (2006), values adjusted to € of 2010
[d]Source: Sultana et al. (2010), values adjusted to € of 2010
[e]Source: Verma et al. (2011)
Table 3. Main case study input data

5.   Results and discussion

The optimum values of the variables found by the optimization model for both cases examined and the financial criteria values are presented in Table 4 and Table 6 respectively.

	Pelleting	CHP
Installed Capacity Co-generation (kW$_{heat}$)	-	6480
Installed Capacity Boiler (kW$_{heat}$)	-	6165
Installed Capacity Pelleting Plant (t h^{-1})	0,948	-
Biomass 1 - Olive tree prunings (t yr^{-1})	2731	2734
Biomass 2 - Almond tree prunings (t yr^{-1})	223	724
Biomass 3 - Apple tree prunings (t yr^{-1})	712	0
Biomass 4 - Peach tree prunings (t yr^{-1})	1512	1512
Biomass 5 - Pear tree prunings (t yr^{-1})	4201	0
Biomass 6 - Cherry tree prunings (t yr^{-1})	1484	10323
Total Biomass Collected (t yr^{-1})	10864	15294
Initial biomass inventory (m^3 at end September)	6778	11704
Initial pellet inventory (t at end September)	3084	-
Longitude of CHP/Pelleting plant (km HGRS 87)	359,015	359,050
Latitude of CHP/Pelleting plant (km HGRS 87)	4397,438	4397,646

Table 4. Optimum solution

The facility locations lie very close to one another and are both located on the lower bound of the proximity constraint of the model (equal to 2 km), obviously in order to reduce the distribution logistics cost for the pelleting case and the district heating pipeline investment cost and energy losses for the CHP case.

It is interesting to note that the CHP case requires about 41% more biomass in total, due to the fact that it also generates electricity apart from heat. Various biomass types are selected, the largest quantities being olive, peach and cherry tree prunings in both cases. Pear and apple tree prunings are also used in the pelleting case. To get a better understanding of the

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significance of each biomass type, Table 5 presents the radius from the respective plant within which biomass will be collected. It should be mentioned that the maximum allowable collection distance has been assumed equal to 40 km. From Table 5 one may notice that the available quantities of olive and peach tree prunings are fully utilised. The reason is that using these two biomass sources has the logistical advantage of extending the collection period, therefore reducing significantly the biomass storage needs.

	1. Olive tree prunings	2. Almond tree prunings	3. Apple tree prunings	4. Peach tree prunings	5. Pear tree prunings	6. Cherry tree prunings
Pelleting	40	14	4	40	8	10
CHP	40	28	0	40	0	18

Table 5. Maximum distance of biomass procurement (km)

	Pelleting	CHP
Profitability Index	6,03	2,95
NPV (10^6 €)	6,51	19.96
IRR	0,64	0,32
Simple Pay Back Period (yr)	1,83	4,02
Total Investment (10^6 €)	1,30	10,22

Table 6. Financial criteria for the optimum solution

The financial criteria of Table 6 suggest that both investment options are attractive, having a Profitability Index greater than one and positive Net Present Value (NPV). However, the Profitability Index, which is the optimization criterion, is much higher for the pelleting plant case. Despite the fact that the NPV of the CHP plant is about three times higher, the significantly higher investment cost required (about eight times higher than the pelleting plant) favours the pelleting plant investment option. The investment analysis based on the Internal Rate of Return and Simple Payback Period criteria confirms the conclusions reached by the Profitability Index.

It is also interesting to analyse the income and cost streams of the investment. In Table 7, the income sources of the cases examined are presented together with the annual amount of the respective energy products. The income from heat sales is practically the same as pellets sales. However, in the case of the CHP plant there exists an extra revenue stream from electricity sales, which corresponds to a value higher than heat sales.

	Amount	Value (10^6 € y^{-1})
Electricity - CHP plant	13724 MWh_{el}	2,76
Heat - CHP plant	33300 MWh_{heat}	1,95
Pellets - Pelleting Plant	6823 t	1,91

Table 7. Products and Income analysis for the optimum solution

Cost breakdown per function	Pellets	CHP
Biomass Purchasing & Loading	52,5%	34,4%
Biomass Transportation	1,6%	1,6%
Biomass Storage	6,1%	11,2%
Pelleting/CHP Plant	29,0%	40,8%

Pellets Storage	5,4%	-
Pellets Distribution	5,4%	-
Heat Distribution	-	10,4%
Electricity Transmission	-	1,6%
Cost breakdown in investment & operation	Pellets	CHP
Investment	10,7%	39,4%
Operational	89,3%	60,6%

Table 8. Cost analysis for the optimum solution

Table 8 shows a significantly different cost structure for the two investments. First of all, the CHP plant itself entails a significantly higher investment cost, reaching 39,4% of the total system cost in the projects' lifetime, whereas the respective value for the pelleting plant is only 10,7%. If further analysed, the CHP plant requires a higher biomass storage cost and a significant cost for the heat distribution infrastructure. The increased biomass storage cost of the CHP plant does not result from higher inventory but from the requirement for a more sophisticated warehouse construction with drying infrastructure, for a specific amount of the biomass inventory. On the other hand, the pelleting plant requires an extra cost for product (pellet) storage and distribution. The biomass transportation is a minor cost in both cases, due to the limited travel distances required. Biomass purchasing and loading cost is more than half the total system cost for pelleting, and is the second most important cost factor for the CHP case.

In Figure 1, the inventory profile for biomass and pellets is presented. The peak of the inventory profile determines the storage space requirements in each case, due to the assumption that dedicated storage space will be used. Biomass inventory is increased steeply during the period of biomass availability, whereas pellet inventory reaches its minimum almost at the end of the heating period. It is very interesting to note that the pelleting plant has been sized to operate in full capacity the whole year, in order to reduce the investment cost and increase the utilisation of equipment, as can be also seen from Figure 2. Therefore, pellets are produced at a fixed rate and are stored when demand is less than production rate. This operational strategy leads to minimum investment cost, which explains the low contribution of investment cost to the total lifetime cost. On the other hand, the heat-match mode operation of the CHP plant means that equipment is utilized only when heat is required by the customers, and therefore operational time is significantly limited, thus limiting capital cost spreading to a shorter operational time-period. This major difference of the two systems may be held responsible for their significantly different financial yield. One way to overcome this problem of CHP technology in countries with warm climates is the use of tri-generation, to allow the unit to operate during summer months, generating cooling and distributing it to the district heating customers. This option has been found to improve the financial attractiveness of a biomass CHP plant (Rentizelas et al., 2009c).
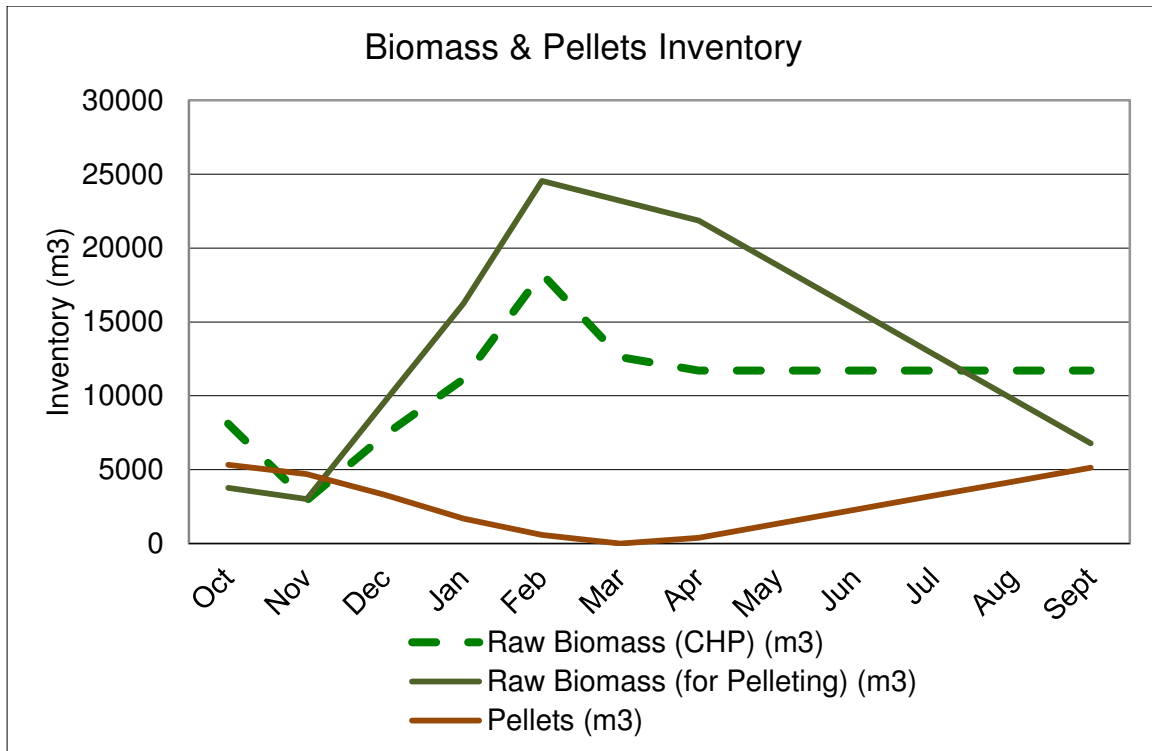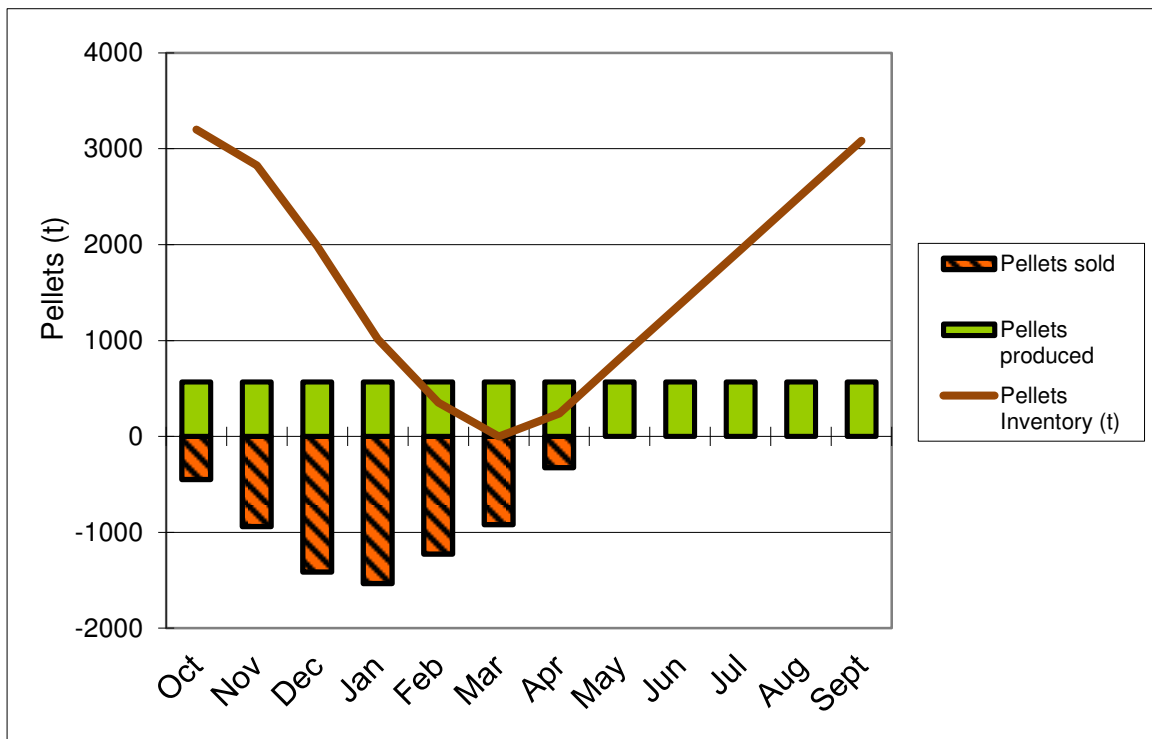
Figure 1. Biomass & Pellets inventory

Figure 2. Pellet production rates, sales rates and inventory

6.   Sensitivity analysis

Most parameters included in the model have a degree of uncertainty. Therefore, a sensitivity analysis of the optimum solution found has been performed in relation to the most important

parameters. Each parameter has been changed within the range of ±50% from the base-case value, in steps of 10%, and the resulting change in the Profitability Index of the investment is presented in Figure 3 for the pelleting plant and in Figure 4 for the CHP plant.
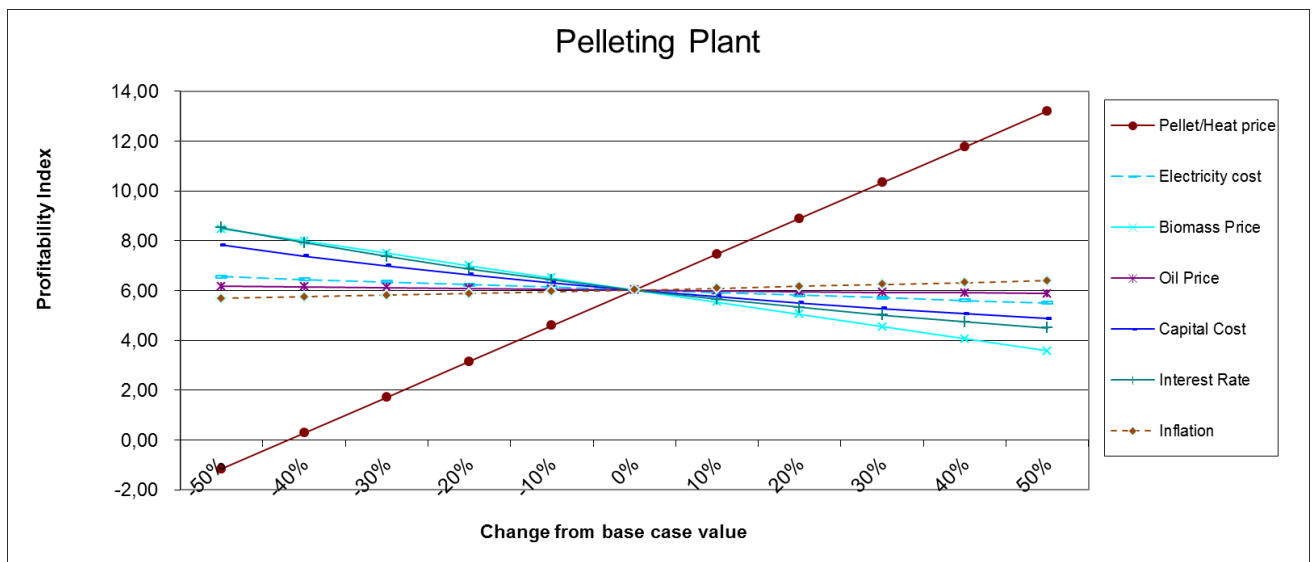

Figure 3. Sensitivity analysis for the pelleting plant

The Profitability Index of the Pelleting plant investment is very sensitive to changes in the pellet price. A reduction of pellet price in excess of about 35% will lead to negative yield of the investment (PI <1). On the other hand, an increase on pellets price may lead to even higher yield of the investment, if the raw biomass cost remains fixed. However, raw biomass price is the most influential cost factor, and therefore care should be taken to secure its price with long-term contracts if possible. From Figure 3, it can be seen that even a change in biomass price up to 50% will not render the investment infeasible, but will reduce the investment yield significantly. The interest rate is almost of equal importance to biomass price. If the real interest rate varies significantly from the 10% value assumed in this work, the potential investors should examine thoroughly its effect. The investment yield is also sensitive to changes in the capital cost of the investment, though to a smaller extent than the above mentioned parameters. Finally, the investment has limited sensitivity to changes in oil price, electricity cost and inflation. The explanation for this is that limited quantities of oil are used (only for biomass logistics, where average travel distances are low due to the local availability of biomass), electricity is used only for the plant operation and not for biomass drying, and inflation has a low base case value.
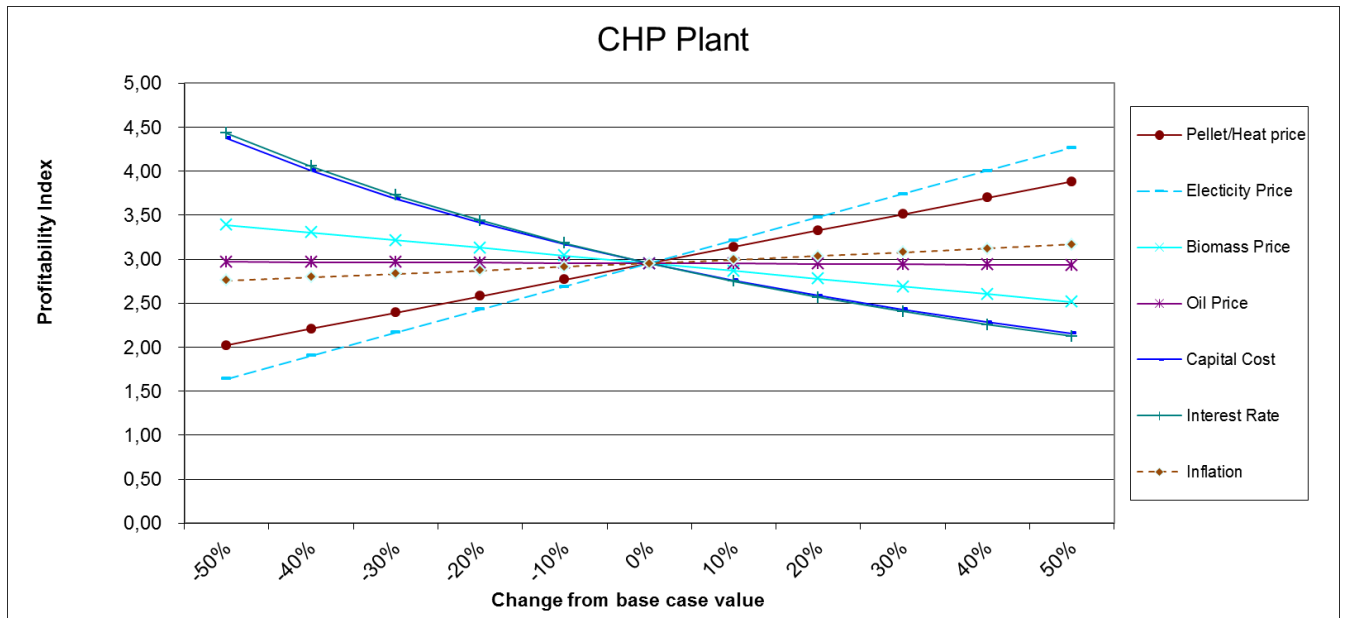
Figure 4. Sensitivity analysis for the CHP plant

The CHP plant investment yield is mostly sensitive to the prices of electricity. In the sensitivity analysis, it has been assumed that the electricity selling price to the grid will change proportionally to the electricity buying price from the grid, which is used primarily for the district heating network operation. It should be noted though that the price for renewably generated electricity is currently regulated by law with long-term fixed price contracts. Therefore, it is expected that this parameter will not pose any significant risk for the investors. The investment yield is also substantially sensitive to changes in the heat selling price, though the sensitivity is significantly lower than in the pelleting plant case. The capital cost and interest rate are the two most significant cost factors affecting the investment yield. Sensitivity on biomass price is lower but still significant, whereas sensitivity on oil price and inflation is almost negligible.

Comparing the sensitivity analyses of the two different investment options, one may infer that the CHP plant is significantly less sensitive in price changes of the energy products generated than the pelleting plant. The latter has much higher yield under the base case parameter values, but the former benefits from simultaneous production of two energy products, therefore securing the investment yield in the case of significant price changes on either of the products. The pelleting plant is thus characterised as a more risky investment, as a reduction of more than 25% in the pellets and heat price will render the CHP plant a more attractive solution. Evenmore, a 35% decrease of pellets and heat price leads to a negative yield for the pelleting plant, while the CHP plant is still an attractive option. Finally, changes in the capital cost affect significantly the CHP investment yield, due to the high initial investment required, whereas biomass purchasing price affects mostly the pelleting plant investment yield, due to the lower value product generated.

7. Conclusions

This work examines comparatively two different energy supply chain options, namely pellet production and Combined Heat and Power generation. The main difference among the two options is that in the pelleting case, production is disengaged from demand, since pellets can be stored. In the CHP case heat has to be generated when demanded, as it cannot be stored in significant amounts and for long time periods. A model has been presented that simulates the

pelleting plant supply chain, both upstream and downstream. The system simulated is optimized in terms of basic design characteristics (location of the facility and capacity of the plant) as well as operational parameters (amounts of each fuel type to use annually). The optimization criterion is the Profitability Index of the investment. The model presented is based on the multi-biomass concept. The model used for the CHP plant case, is a modification of the model presented in the work of Rentizelas et al. (2009a).

The models have been applied to a case study region in Greece. The results show that both investments have positive yield, though the pelleting plant investment appears to be much more attractive in financial terms. However, the sensitivity analysis has determined that the pelleting plant investment yield is highly sensitive on the pellet price, and that a reduction of more than 25% of this value will make the CHP plant a better investment option. Actually, the CHP plant appears to be a lower risk investment, due to the simultaneous production of two energy products and the current legislation providing long-term fixed prices for renewable electricity generation. On the cost-related parameters side, the pelleting plant investment yield is mostly sensitive on the biomass purchasing price, whereas the CHP plant is mostly sensitive on the capital cost. Both cases have a high sensitivity to the interest rate.

The results of this work indicate that pellets are a more attractive solution, in financial terms, for an investor willing to engage in the biomass energy sector, compared to centralised CHP generation. If conventional fuel source prices continue to increase, pellet price may also increase, thus further increasing the attractiveness of investing in a pelleting plant using locally available biomass sources. It should be noted however that the findings of this work apply only to the production rates and plant sizes examined for the case study region and that the results could be significantly different if the scale of the investment changes. The main reason for this is that the effect of scale economies is expected to be higher for the CHP plant.

The fact that both supply chains appear to have very positive financial yield denotes the potential for profit generation. Therefore, energy exploitation of locally available biomass sources is expected to increase in the future, leading to a need for local biomass supply chain organization. Finally, it becomes apparent from this work that there is a great opportunity in exploiting agricultural residue biomass sources that have not been used up to now.

8.   References

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Figure Captions

Figure 1. Biomass & Pellets inventory

Figure 2. Pellet production rates, sales rates and inventory

Figure 3. Sensitivity analysis for the pelleting plant

Figure 4. Sensitivity analysis for the CHP plant