Assessing the sustainability of biomass supply chains for energy exploitation

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Abstract

Biomass use has increased significantly lately, partly due to conventional fuels price increase. This trend is more evident in rural areas with significant local biomass availability. Biomass may be used in various ways to generate heat.

In this work, the focus is on comparing two different biomass energy exploitation supply chains that provide heat at a specific number of customers at a specific cost. The first system is pellets production from biomass and distribution of the pellets to the final customers for use in domestic pellet boilers. The second option is centralized energy co-generation, which entails simultaneous electricity and heat generation. In the latter case, heat is distributed to the customers via a district heating network whereas electricity is fed to the electricity grid. The biomass source examined is locally available agricultural residues and the model is applied to a case study region in Greece.

The aim of this work is to determine how these two different biomass exploitation options perform in sustainability terms, including the economic, environmental and social dimensions of sustainability. The effect of trying to optimise separately the economic and environmental dimensions of sustainability on the system design is examined, while at the same time taking into account the social dimension. Furthermore, a bi-objective optimisation is employed, to overcome the limitations of the single-objective optimisation. Both the upstream and the downstream supply chains of the pelletizing/CHP units are modelled.

Keywords: Sustainability, Biomass, Pellets, Combined Heat and Power, Electricity generation, Logistics.

1. Introduction

The issue of sustainable production has gained significant attention during the last years. Sustainability is a concept incorporating corporate performance against three dimensions: economic, environmental and social (Elkington 1997). Most of the research traditionally performed would examine only one of the three dimensions, ignoring the others to a large extent. Therefore, overall optimal solutions for production systems in terms of sustainable performance could not be identified. Sustainability in energy generation in particular has begun to receive significant attention lately, as energy generation is one of the sectors with the highest environmental effects, while at the same time it is a primary financial sector serving basic human needs that significantly affect their living standards.

Renewable energy resources seem to be one of the most efficient and effective solutions for satisfying the future energy needs (Kaya 2006). Biomass is a renewable energy source that has been used by mankind since the ancient times. Lately, biomass has gained significant attention, due to the necessity of reducing atmospheric CO_2 emissions and the technological improvements in biomass energy conversion. Modern biomass chains are considered to be ‘carbon neutral’ or even ‘climate neutral’, meaning that they are considered to have a neutral impact on the biogeochemical carbon cycle or on climate (Cornelissen and Hirs 2002). 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.

Although biomass is considered to be a ‘carbon neutral’ fuel source, since using it for energy generation emits the same amount of carbon that the plants have absorbed while growing, there are processes required that use conventional fuel sources (e.g. logistics of biomass, pelleting) or require the use of other resources that might have an adverse impact on the environment and human health (pesticides, fertilisers etc). Furthermore, biomass production and use could potentially have positive or negative social effects when performed in large scale, such as employment levels, health effects, noise from transportation, visual impact, loss of biodiversity etc. Therefore, the sustainability of using biomass for energy generation purposes cannot be considered as a given.

This work aims to examine how two different biomass exploitation systems perform in sustainability terms. More specifically, two different biomass supply chain and energy exploitation options are compared in terms of the three dimensions of sustainability, namely the environmental, economic and social. The ultimate aims are to identify the optimum system design if each of the dimensions is addressed in isolation, in order to examine the resulting differences in the system design, and to subsequently investigate if there can be a single optimum design that maximises the overall sustainability performance. The work is exploratory in nature and is therefore not considered to be a complete and systematic approach; rather, it is the first stage of an ongoing research. Both the upstream and the downstream supply chains of the two systems examined are modelled.

2. Literature Review

The topic of energy recovery from biomass has been extensively researched in past (Mitchell et al. 1995) as well as in more recent studies (Rentizelas and Tatsiopoulos 2010). The major restricting factor in biomass energy recovery is the biomass supply chain; therefore several models concerning the supply chain of biomass have been published. Caputo et al. (2005) concluded that 56–76% of the total system operational costs are due to the biomass logistics, thus indicating the potential for cost reduction. The case of biomass-fired plants, producing combined heat and power (CHP), has been researched in the literature (Tatsiopoulos and Tolis 2003; Pantaleo et al. 2009), whilst the case of energy tri-generation has been also investigated (Rentizelas and Tatsiopoulos 2010). The concept of the exploitation of multiple biomass feedstocks has recently emerged, providing interesting alternatives to conventional single-biomass sourcing strategies (Rentizelas, Tatsiopoulos, et al. 2009; Rentizelas, Tolis, et al. 2009). In many instances, optimisation methods have been employed to optimise logistics activities of biomass (Cundiff et al. 1997), the transportation distance (Papadopoulos and Katsigiannis 2002) and even the energy supply at a regional level from forest biomass (Freppaz et al. 2004).

Lately, the issue of questioning and determining the sustainability of generating energy from biomass has appeared in the relevant literature. In fact, Burritt and Schaltegger (2012) state that it is not possible to conclude in general terms that industrial production and use of biomass is sustainable and that accounting for biomass must recognise the broader ecological and social system of which the production and use form a part. Zhang and Long (2010) criticise the classic methods that relate to energy or economic assessment, since assessing environmental sustainability requires a more integrated analysis. According to Zhang and Long (2010), the emergy analysis is considered as a more appropriate approach for quantifying environmental and economic effects. Emergy analysis assesses all the inputs that supply a system, focusing also on those that are usually neglected by classic economic accounting methods, giving an appraisal of the actual environmental cost of any class of resource that is not limited to its economic price or energetic content (Pulselli et al. 2008).

According to Pavanan et al. (2013), the most common tool used for sustainability measurements is Life Cycle Analysis (LCA). For example, LCA was used by Gilbert et al. (2011) to examine the current agronomic practice in the UK for Short Rotation Coppice (SRC) willow and miscanthus energy crop production. Pavanan et al. (2013) state though that LCA is not relevant to financial and social criteria, and is therefore suboptimal for measuring biomass sustainability. Several other tools such as the Living Planet Index (LPI), City Development Index (CDI), Human Development Index (HDI), and Environmental Performance Index (EPI) are found to often fail to meet scientific criteria. Pavanan et al. (2013) suggest the use of the Total Factor Productivity (TFP) to provide a single index of sustainability of commodities based on price-related productivity measures.

3. Modelling Approach

In this work, two different biomass-to-energy supply chains are examined. The first one concerns collecting biomass to produce pellets, which are then distributed to consumers for domestic heat generation. The second one concerns using the same biomass sources in a CHP unit to generate electricity and heat. Electricity can be supplied to the grid, whereas heat can be distributed via a district heating network for residential use. To have a common basis of comparison, the system is considered in both cases to be demand-driven, meaning that the target is to supply heat to an existing heating demand, namely to the same number of final consumers. In reality though, the pelleting plant would be much more flexible in serving heating needs over larger distances than the CHP plant, which requires the existence of a heat distribution network.

An effort has been made to use boundaries for the systems examined that are 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. Although the cost of these operations is included in the biomass purchasing price, the related conventional fuel consumption and greenhouse gas emissions are not included in this study. 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 consumers' heat metering point. Various forms of tree prunings have been considered as potential biomass source, as this type of agricultural residue seldom finds an alternative use and it is a wood biomass, which is compatible with the existing pelleting and CHP technologies.

The multi-fuel concept is adapted from the multi-biomass model of Rentizelas et al. (2009). The model presented by Rentizelas et al. (2009) has been adapted and used for the case of the CHP plant. The model used for the pelleting case is adapted from (Rentizelas et al. 2013). Various modifications have been made to the abovementioned models, in order to be suitable for use in this work. The main modifications are described below.

This work examines the effect that focusing on each one of the three sustainability dimensions would have on the system design. Therefore, a different model has been used for each dimension, as described:

- For the economic dimension of the sustainability, it has been assumed that the optimum system design in each case is the one that maximises the financial return of the investment. The criterion used is the Profitability Index, in order to allow comparison of two investment options with significantly different investment cost. When examining the economic dimension of the sustainability, the objective function of the optimisation problem to be maximised is set as the Profitability Index of the investment.

- For the environmental dimension of the sustainability, the optimum system design is the one that minimises the greenhouse gas emissions from downstream and upstream logistics operations. More specifically this means biomass transportation from fields to the power/pelleting plant and biomass handling, as well as the delivery of energy products, which means road transportation in the case of pellets or electricity used for pumping hot water via the district heating network in the CHP case. When examining the environmental dimension of the sustainability, the objective function of the optimisation problem to be minimised is set as the total upstream and downstream logistics greenhouse gas emissions.
- For the social dimension of sustainability, the criterion used was the proximity of the CHP/pelleting plant to the municipality with the final heat consumers. Biomass-to-energy facilities are in many cases considered as semi-desirable or semi-obnoxious facilities (Upreti 2004). The potential reasons for this perception are increased local traffic from biomass transportation activities, visual nuisance, and fear for health effects. Therefore, the proximity of these facilities to local communities is a factor that may significantly determine its social impact. In this work there was no straightforward way to quantify the social effects and model them as the objective function of an optimisation model. For this reason, it has been chosen to model the social impact as a constraint with two different levels of minimum distance between the CHP/pelleting plant and the case study municipality.

The notation used in the results section for each of the various scenarios is X/Y/Z where:

- X may take the value “Pel” if a pelleting plant is considered, or “CHP” if a cogeneration plant is considered.
- Y may take the value “PI” if the economic criterion of Profitability Index is maximised, or “G” is the environmental criterion of logistics greenhouse gas emissions is minimised.
- Z refers to the social impact, which may take the values “Sh” for high social impact, if the minimum Euclidean distance between the plant and the local community is set to its lower value (0.5 km), or “Sl” for lower social impact, if the minimum Euclidean distance is set to its higher value (2 km).

The model used for the CHP plant with the economic optimisation criterion can be found at Rentizelas et al. (2009), while the respective model used for the pelleting case with the economic optimisation criterion can be found at Rentizelas et al. (2013). In the case of the environmental criterion optimisation, the objective function of the optimisation problem has been modified: In the case of the CHP plant, it is

$$Z_{Env\text{-}CHP} = Gtot_{log\text{-}CHP} = Gb_{tr} + Gb_h + Gel_p \ , \qquad (1)$$

and in the case of the pelleting plant

$$Z_{Env\text{-}Pel} = Gtot_{log\text{-}Pel} = Gb_{tr} + Gb_h + Gpel_{tr} \ , \qquad (2)$$

where $Gtot_{log}$ are the total upstream and downstream logistics-related greenhouse gas emissions, Gb_{tr} is the raw biomass transportation from field to CHP/pelleting plant- related greenhouse gas emissions, Gb_h is the biomass handling-related greenhouse gas emissions, Gel_p is the greenhouse gas emissions related to electricity consumed to operate the district heating pumps, and $Gpel_{tr}$ is the emissions related to pellets transportation from the pelleting plant to the final consumers.

4. Case Study

The case study is a municipality in Greece, located in the plain of Thessaly, where several types of agricultural residue biomass are locally available. Tree prunings have been considered as raw material for pellet production or CHP generation. The reason for including only woody biomass types is to ensure compatibility of the biomass logistics processes and equipment as well as the pelleting plant equipment with all biomass types examined. Tree prunings are characterised by seasonality, arising from time restrictions associated with the agricultural operations for the primary products. The district energy customer will be the citizens of a local community 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. No subsidies of any kind have been included in the case study when performing the economic analysis.

Revenues of the CHP facility 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.

5. Results and Discussion

5.1 Single-objective optimisation. The first set of results has been obtained by optimising a single objective each time. The first objective is maximisation of the financial return of the investment, expressed in the form of the Profitability Index. The second objective is the minimisation of the environmental effect of the system, expressed as the CO_2 emissions of the logistics functions, including both the biomass and the product distribution-related emissions. The social aspect of sustainability has not been modelled as an optimisation objective; rather as a constraint (distance of biomass plant from the local community using the energy products) that is relaxed in some scenarios, in order to examine its effect. The optimisation variables are presented in table 1.

From Table 1 it can be seen that the technical characteristics of the optimum system identified are not the same in all scenarios. A significant difference can be identified in the case of CHP, where the peak-load biomass boiler is larger in capacity and the base-load co-generation unit is smaller, when the objective is to minimise the logistics-related emissions. This system design leads to lower electricity generation and subsequently to lower biomass consumption, therefore reduced logistics operations required. This can also be verified by the total biomass collected annually in each scenario. In addition, depending on the scenario examined, the proposed location of the facility changes, therefore leading to different optimum biomass mix. In the case of a pelleting plant, there are no major differences, apart from the fact that the plant capacity is increased, when the objective is to minimise the logistics-related emissions. Furthermore, small variations in the biomass mix used can be identified.

	Pel/PI/Sh	Pel/PI/Sl	Pel/G/Sh	Pel/G/Sl	CHP/PI/Sh	CHP/PI/Sl	CHP/G/Sh	CHP/G/Sl
Installed Capacity Co-generation (kW heat)	-	-	-	-	3868	3902	1943	808
Installed Capacity Boiler (kW heat)	-	-	-	-	4625	4625	4998	5000
Installed Capacity Pelleting Plant (t/h)	0.93	0.95	1.18	1.16	-	-	-	-
Biomass 1 - Olive tree prunnings (t/y)	2734	2733.80	2164.91	2280.55	2734	0.82	683.96	1380.19
Biomass 2 - Almond tree prunnings (t/y)	117	154.85	105.26	4.76	0	3402.56	14.70	0.10
Biomass 3 - Apple tree prunnings (t/y)	689	204.28	359.86	1848.90	0	1003.45	2376.54	2682.41
Biomass 4 - Peach tree prunnings (t/y)	1512	1512.48	96.19	94.62	1512	1504.47	165.20	0.14
Biomass 5 - Pear tree prunnings (t/y)	312	5630.29	6693.16	5233.93	0	2556.69	8060.85	2619.83
Biomass 6 - Cherry tree prunnings (t/y)	5232	680.52	1596.60	1567.74	11847	8091.95	3204.70	6163.30
Total Biomass Collected (t/y)	***10596***	***10916***	***11016***	***11030***	***16094***	***16560***	***14506***	***12846***
Longitude of CHP/Pelleting plant (km in HGRS 87)	360.6	357.4	359.60	359.25	359.76	358.475	361.41	359.38
Latitude of CHP/Pelleting plant (km in HGRS 87)	4400.2	4399.7	4399.48	4397.76	4398.98	4398.17	4398.08	4401.23

Table 1. Values of optimisation variables

In Figure 1, one can see the value of the Profitability Index (PI) for all the scenarios examined. It can be seen that the value of the PI is significantly reduced if the optimisation criterion is the logistics greenhouse gas emissions instead of the PI, for all the scenarios examined. It can also be noticed that the constraint modelling the social aspect of sustainability (the distance of the plant from the consumers' location) does not affect noticeably the financial yield of the investment in the case of a pelleting plant, whereas it has some effect in the CHP case. In the latter case, imposing a higher distance of the plant from the consumers' location leads to lower financial yield.

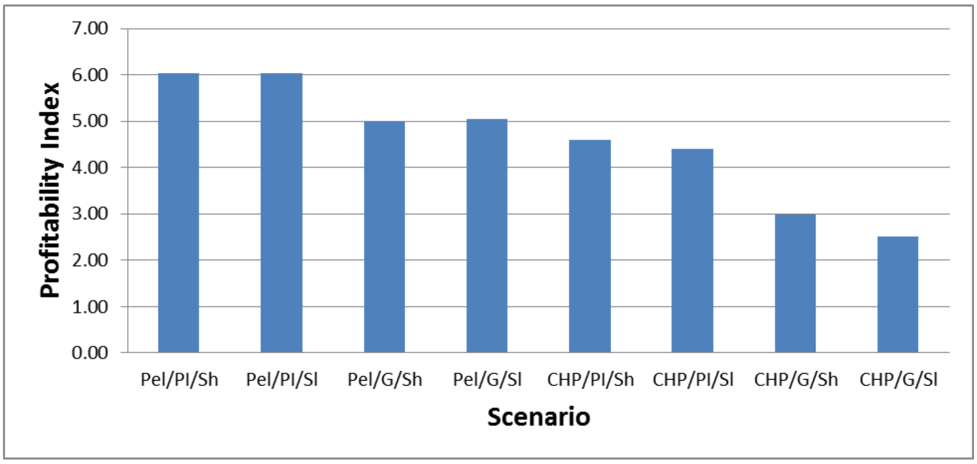

Figure 1. Profitability index for scenarios examined.

Figure 2 presents the logistics-related greenhouse gas emissions for both biomass and the energy products, for all scenarios. It is obvious that all scenarios having the objective function of minimising the greenhouse gas emissions lead to lower emissions compared to the scenarios with the objective function of maximising the financial yield. Therefore, it can be concluded from Figures 1 and 2 that the two objectives are conflicting. Scenarios involving electricity and heat co-generation (CHP) lead to significantly higher logistics emissions, primarily because the yearly amount of biomass used is higher, in order to generate electricity in addition to heat. It should also be noted that the absolute value of logistics greenhouse gas emissions is very low, due to the fact that biomass is locally available in the vicinity of the final customers. This is explained in more detail in Figure 3: scenarios aiming at minimum logistics-related greenhouse gas emissions lead to roughly half the average biomass collection distance, compared to the same scenarios aiming to maximise the financial yield. Thus, it can be concluded that the logistics-related emissions can be significantly reduced by varying the biomass mix chosen to minimise the logistics function or by altering the system design characteristics, but at a significant negative impact at the financial yield of the project.

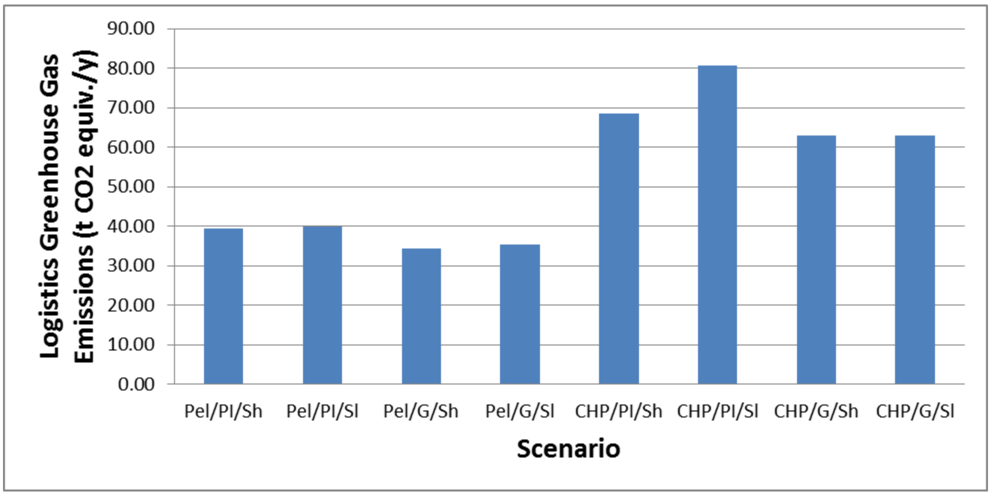

Figure 2. Biomass and product logistics greenhouse gas emissions for scenarios examined.

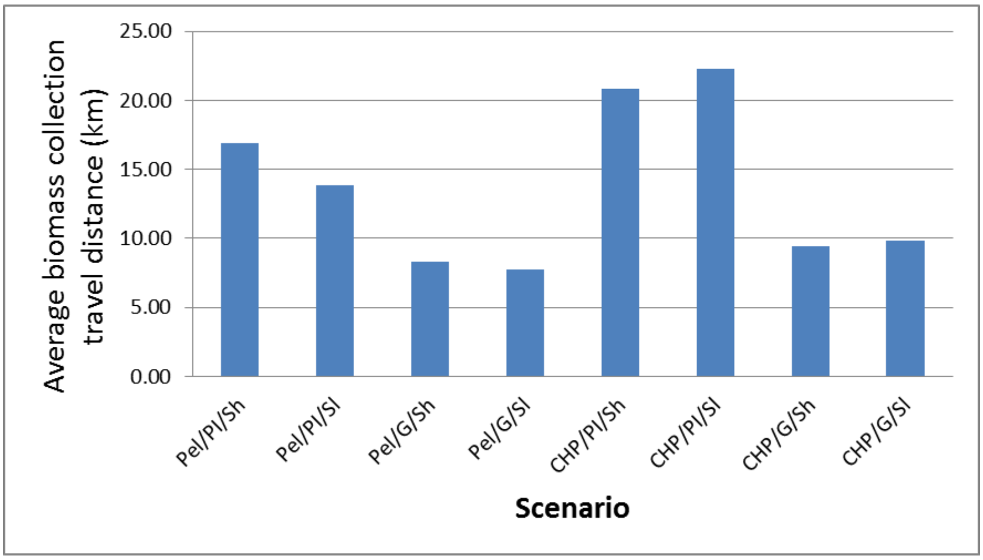

Figure 3. Average biomass collection travel distance for scenarios examined.

The production of pellets entails the logistics functions of storing the pellets and transporting them to the final consumers. It can be noticed that when the social constraint is relaxed (i.e. when the plant is allowed to be constructed closer to the final consumers' location), the model proposes indeed a much nearer plant location (scenarios noted "Sh" in Figure 4). It can also be noticed that when the minimisation of logistics-related greenhouse gas emissions is aimed, the plant location is closer to the customers' location. Figure 4 shows the actual travel distance.

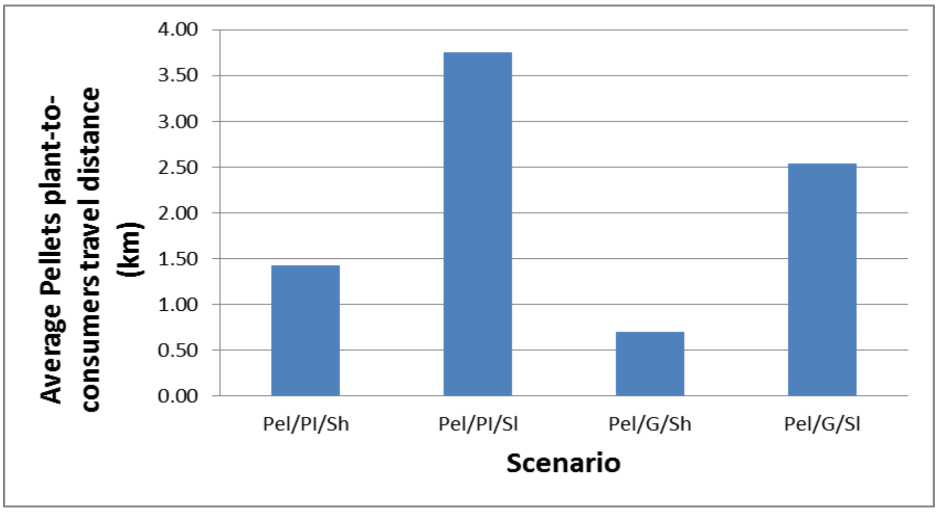

Figure 4. Average pellets plant-to-consumers travel distance for scenarios examined.

Figure 5 presents the Euclidean distance between the plant and the final consumers' location for both technologies (pellets and CHP). Similarly to the case of Figure 4, it can be concluded that when the social constraint of minimum distance between plant and consumers is relaxed, a plant location closer to the final consumers is chosen in most cases.

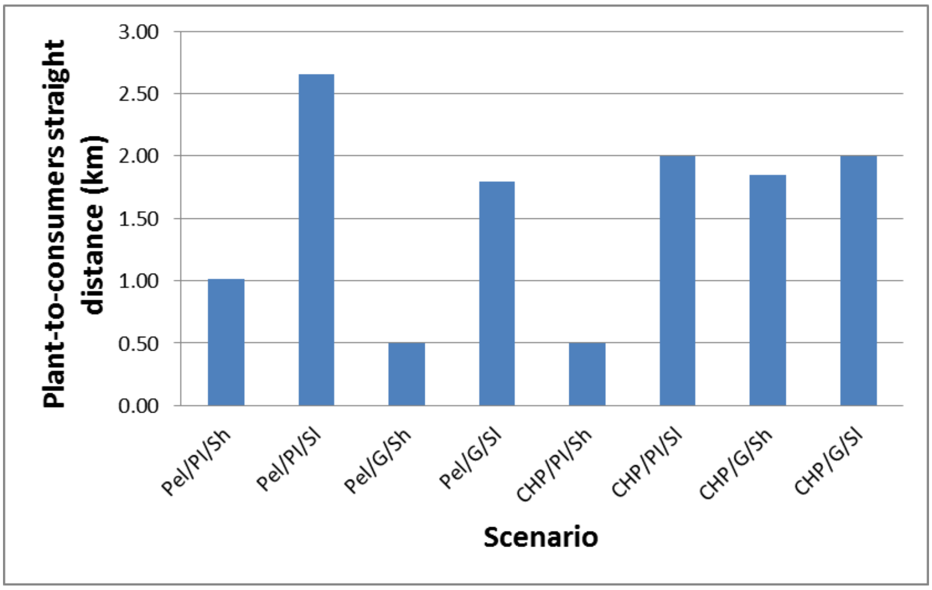

Figure 5. Plant-to-consumers Euclidian distance for scenarios examined.

Biomass is considered to be a carbon-neutral energy source. Therefore, using it for energy production, either in the form of heat or electricity means it will substitute energy that would be generated by other means. In this case study, the base case is that electricity is supplied by the national grid, primarily generated by fossil fuel sources, and heat would be generated using diesel oil in household boilers. Using energy generated from biomass can lead to significant greenhouse gas emissions reduction, which are presented in Figure 6. The added greenhouse gas emissions due to biomass and final energy products logistics have been subtracted. It can be observed that the CHP scenarios lead to significantly higher emissions reduction compared to the pelleting scenarios, due to the fact that there is also renewable electricity generated apart from heat. However, the higher emissions reduction is achieved in the cases where the financial yield of the investment is maximised, as the system generates as much renewable energy as possible in order to increase the profits. On the other hand, when trying to minimise the logistics-related greenhouse gas emissions, the electricity generation is reduced, in order to reduce the total amount of biomass collected and transported (see also Table 1). The amount of emissions reduction achieved in the "PI" scenarios is at least two orders of magnitude greater than the additional logistics-related emissions, which means that in reality, a systems perspective should be adopted; emissions from biomass logistics operations should not be treated in isolation, as the effect on the environmental performance of the system as a whole could be jeopardised. Figure 7 provides a quantified metric for this, as it reveals that every ton of CO_2 emitted by biomass and final product logistics corresponds to 187-330 tons of CO_2 saved due to substituting energy from conventional sources with renewable energy. It should be noted though that this is not a complete metric, as the emissions during biomass cultivation and collection are not included.

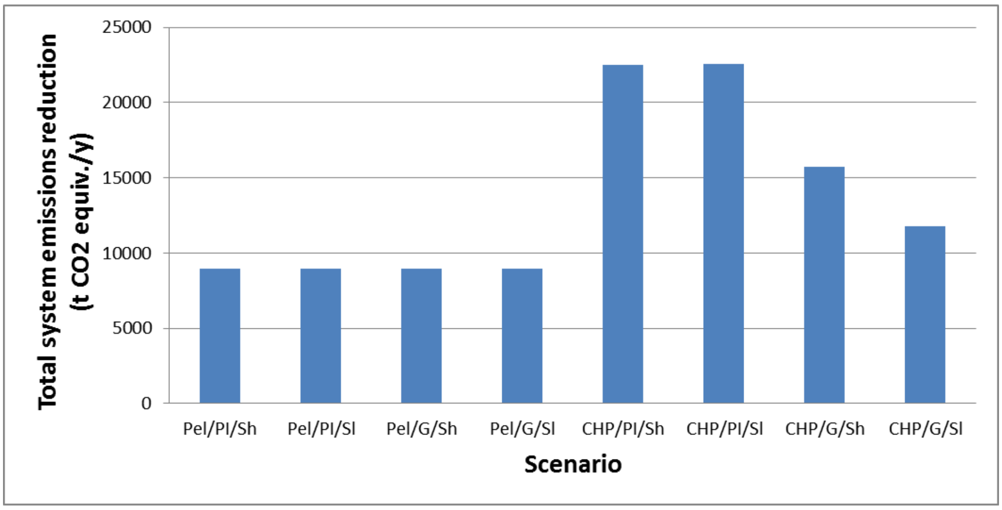

Figure 6. Total system greenhouse gas emissions reduction for scenarios examined.

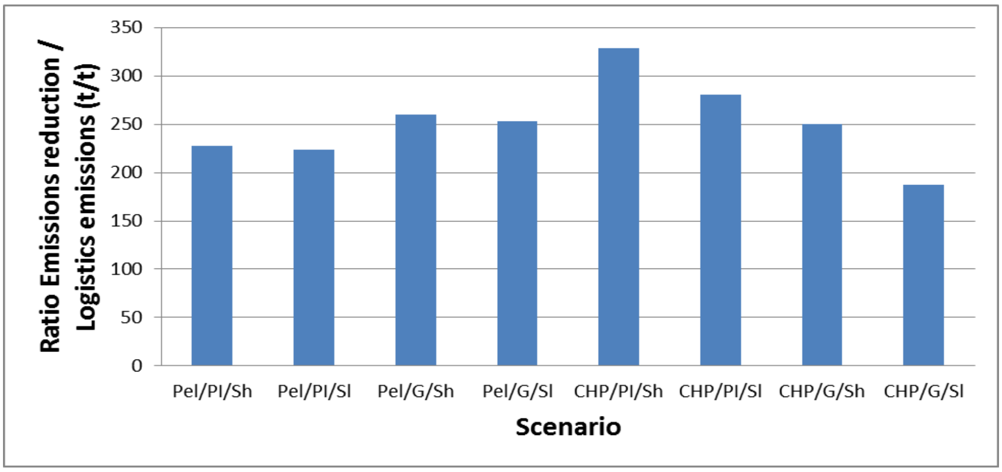

Figure 7. Ratio of system greenhouse gas emissions reduction to logistics emissions for scenarios examined.

5.2 Multi-objective optimisation. Due to the fact that the two objectives examined were found to be conflicting (financial yield and logistics-related emissions), a bi-objective optimisation technique has also been employed. The new bi-objective function is a linear combination of the financial and the environmental objective functions:

$$Z_{Bi} = \alpha^* Z_{Fin} + (1-\alpha)^* Z_{Env}, \quad 0 \leq a \leq 1. \tag{3}$$

The parameter α takes any value between 0 and 1, therefore attributing higher weight to the environmental or the financial objective respectively. The two objective functions, Z_{Fin} for maximising the financial yield and Z_{Env} for minimising the logistics-related emissions have been normalised in this case. Several runs of the model were performed for the whole range of the values of parameter α, and the results are presented in Figure 8 for the CHP case and in Figure 9 for the pelleting case.

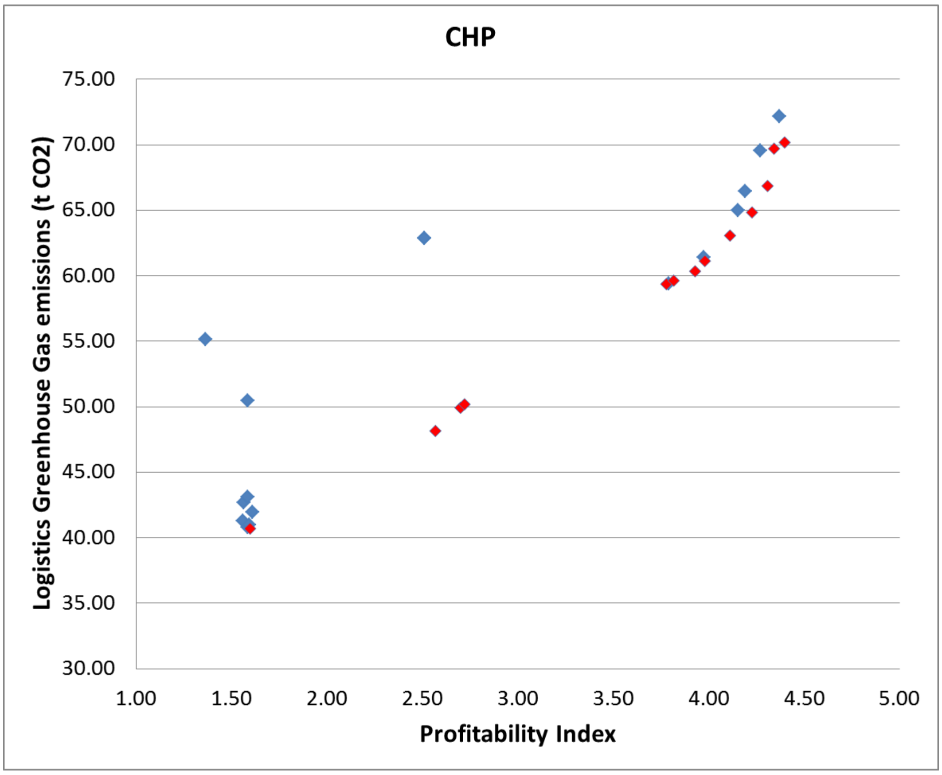

Figure 8. Multi-objective optimisation results for profitability index and logistics greenhouse gas emissions, for the case of CHP. The Pareto front is denoted in red.

The pareto front of the pareto-optimal solutions is apparent in Figure 8 and is denoted with red dots. This means that all solutions not belonging to the pareto front are inferior to another solution belonging to the pareto front in at least one of the objectives. All pareto-optimal solutions are optimum in the sense that there can be no other solution qualifying better in both objectives, or even in one objective, the other being equal. A decision-maker would choose solutions belonging to the pareto front. It can be concluded that a decision-maker could choose solutions that reduce the logistics-related greenhouse gas emissions, but at a severe expense to the profitability. In reality, the logistics-related emissions reduction is minor compared to the financial impact this rediction could have. In Figure 9, the pareto front for the case of the pelleting plant is presented. The finding is similar to the CHP case: the decision-maker can find alternative pareto-optimal solutions to reduce the logistics-related greenhouse gas emissions, but at a severe expense to the profitability.

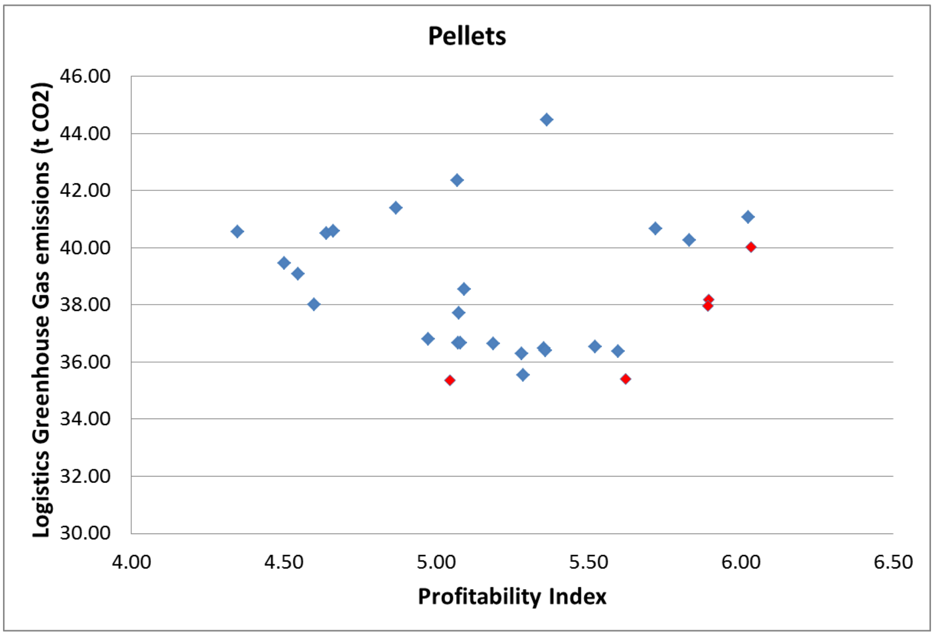

Figure 9. Multi-objective optimisation results for profitability index and logistics greenhouse gas emissions, for the case of Pellet production. The Pareto front is denoted in red.

6. Conclusions

The focus of this work has been on assessing how the supply chain design of two different biomass-to-energy options affects its sustainability performance. Sustainability is a term with three distinct dimensions, namely economic, environmental and social. This work has assessed the economic and environmental performance by performing single-objective optimisation, in terms of the financial yield of the project (Profitability Index) or environmental performance (greenhouse gas emissions of biomass and final products logistics). The social aspect has been modelled as a constraint (minimum distance of the plant from the local community), which is subsequently relaxed, to examine its effect.

The primary finding of this process is that using a different optimisation criterion leads to a significantly different system design. Trying to minimise the logistics emissions leads to a disproportionate reduction in the financial yield of the project. Furthermore, it was found that focusing on reducing the logistics-related emissions is actually a fallacy, since the emissions reduction from generating renewable energy to substitute energy generated by conventional fuel sources is by far greater than the related logistics emissions. In some of the CHP cases examined, minimising the logistics greenhouse gas emissions resulted in lower electricity generation, which leads to lower system-wide reduction of greenhouse gas emissions in the atmosphere. Therefore, a systems perspective should be adopted. Relaxing the constraint of minimum distance of the plant from the local community does not change radically the results: The model proposes locating the facility closer to the local community when the constraint is relaxed, thereby reducing emissions from the final product distribution. However, the total logistics greenhouse gas emissions are not significantly affected in most cases examined.

Since the single-objective optimisation fails to provide a holistic solution to the problem of improving the biomass supply chain sustainability, this work has introduced a bi-objective optimisation, where the economic and environmental criteria were given various weights and were combined in a single objective function. Performing several runs for various values of weights led to the development of a pareto front, identifying alternative pareto optimal solutions for the decision-makers. The main conclusion of the bi-objective optimisation is that the decision-makers may choose alternative solutions that are aligned with their priorities, but the gain in greenhouse gas emissions reduction from the logistics operations is very disproportionate to the reduction of financial yield. Finally, the finding that the system-wide emissions reduction should be examined instead of only the logistics-related emissions applies also in this case.

Finally, it should be noted that this work was exploratory in nature and aimed at exploring the difference in the optimum system characteristics, if each of the sustainability dimensions is treated in isolation. The conclusion drawn is that all the sustainability dimensions should be taken into account when designing a biomass-to-energy system. As a further research suggestion, it would be interesting to examine the sustainability performance of biomass energy exploitation including also the stages of biomass cultivation and collection, which were not included in this study. It would be useful to come up with a methodology that would be able to incorporate and assess a variety of criteria for each one of the sustainability dimensions, since the selection of a single criterion can be misleading, as shown in this work for the logistics greenhouse gas emissions criterion.

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