Economic and Environmental Performance of Agro-Energy Production Chains

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Abstract

The design and implementation of agro-energy production chains make some important questions risen about their economic and environmental sustainability, related to aspects such as the yield of the different types of crops, the transportation infrastructure availability, the land dispersion (with the consequent logistics problems), the balance between crops devoted to food or energy production, and the exploitation of land and natural resources. Therefore, suitable key performance indicators need to be provided in order to evaluate the effectiveness and efficiency of agro-energy production, from both the economic and environmental points of view.
With this regard, in this paper an Enterprise Input-Output (EIO) approach is adopted for describing the agro-energy production chains and measuring its performance. The production chain is represented as a network of processes. Indicators about the CO_2 balance, the food vs. bio-fuel production, the net energy production, the imports and exports of energy and fuel, the workforce level, and the value added are identified and analysed.
EIO models can be useful both as an accounting tool, to compute all the materials and energy flows, and as a planning one, to evaluate and compare the performance associated to different scenarios.
Finally, some examples are provided in order to investigate how spatial, technical, and economic issues can differently affect the economic and environmental performance of agro-energy production chains.

Keywords: agro-energy production chain, economic and environmental performance, enterprise input-output.

1. Introduction

In the present economic scenario, the notion of sustainable development has received an increasing attention by scholars, policy makers, and managers. In fact, nowadays, problems related to the natural resources consumption, energy use, Greenhouse Gas (GHG) emissions, and fossil fuel utilization are becoming always more crucial and relevant. With this regard, the transformation of biomass in energy and fuel has been considered as an interesting option for promoting the sustainable development, taking also into account the opportunity to favour the economic growth of rural areas.
Bioenergy production as heat, electricity, and liquid fuels represents about 14% of the world's primary energy supply. About 25% of the usage is in industrialised countries and the other 75% is used in developing countries (Parikka, 2004). In 2005, about 2% of the world's gasoline market and 0.2% of the world's diesel market were supplied by biofuels and there is substantial potential to reduce costs of all biofuel production processes by 2030 (IEA, 2006). The International Energy Agency (2007) estimates total biomass potential in the world to range between 10 and 20 % of primary energy supply by 2050.
In contrast to the local nature of all other renewable energy sources, biomass and biofuels are traded on local, national, and international markets. However, all local markets are expected to play a major role in the future, as environment- and food-oriented policies are becoming more bunding (Widenoja and Halweil, 2008).
By its very nature, bioenergy cuts across several policy areas in addition to energy policy, including agriculture and forestry, environment, employment, trade and market, tax, and rural development.
In particular, bioenergy has the potential to make a significant positive contribution to the climate problem and to provide a source of income to support rural livelihoods (FAO, 2000). To be consistent with sustainable development goals, a concerted move towards sustainable agriculture is needed. In particular, markets have to be redesigned to benefit the rural poor population in the developing world, to provide more employment opportunities and better terms of trade.

In this context, a very important role is played by the local (regional) government, which has to define and support the most effective development trajectories to be undertaken. In fact, a bioenergy production chain cannot be designed and implemented independently from the local development plans and strategies. In fact, it is necessary, for instance, to plan the increase of local biomass production in order to permit the supply to the conversion plants, to reinforce the contractual power of the local biomass producers, and to set the output mix “food/bioenergy”. This seems particularly crucial for the crops which contribute to the food market (e.g. corn, sunflower, wheat, soybean) and are suitable for agro-energy production (i.e. bioenergy production based only on agricultural products), according to a sustainable scale of intervention. In fact, if not carefully evaluated, agro-energy chain could lead to a further degradation of land, water bodies, and ecosystems.
Because of limited availability of land, one can foresee a future in which biomass for energy must be balanced[1] against the need for food, materials, bio-chemicals and carbon sinks. In fact, a large debate (see, for instance, Hoogwijk et al., 2005; Ignaciuk et al., 2006; Kleiner, 2007) about the global efficiency and effectiveness of the use of biomass to produce energy is arising. Questions like the use of crops for energy instead of food (Smil, 1983; Pimentel, 2002; Brown, 2006; UN, 2007; IMF, 2008) or the true amount of net GHG emissions or the appropriate size and dispersion of land required to produce energy or the impact of transportation are some issues of the debate. These concerns need to be addressed with an overall systems approach. Then, suitable and integrated tools able to take into account energy and materials flows as well as the value added for the area (farmers, etc.) are required.
In this paper we focus on the analysis of economic and environmental performance measures of agro-energy production chains. A bioenergy production chain is defined as the network of processes, such as biomass production, transportation, energy conversion, which transform biomass into bio-fuels and/or bio-electricity. Chain performance depends on the type of biomass, land availability and use, farm dispersion, transportation infrastructure, and logistics service. Suitable models, where spatial variables are included, are proposed using the Enterprise Input-Output (EIO) approach. The spatial variables considered are the total cultivation area, the distance between each area and the energy conversion plant, the accessibility of each area. Performance measures such as the CO_2 emissions, the output mix (food, biofuel, electric energy), and the profit in the area are defined and computed. Being food, biodiesel, and bio-electricity the three main outputs, four cases will be examined: energy-balanced (i.e. the energy required by the chain processes is produced within the chain using biomass), food-oriented (only food is produced), biodiesel-oriented, and bioelectricity-oriented.
An actual case study for sunflower-based production chain in the Puglia (Southern Italy) region is proposed and discussed.

2. Spatial Aspects of Agro-energy Production Chains

The agro-energy production chain is the long and complex sequence of activities such as planting, growing, harvesting, pre-treatment (storage and drying), upgrading to a fuel, and finally mechanical, thermomechanical or biological conversion to an energy carrier (electric energy, heat or bio-fuels for transport). Four main processes can aggregate the above activities: cultivation, bio-fuel conversion, agro-energy production, and transportation. This is an essential and, in some cases, expensive process being primary inputs, crops, bio-fuels and by-products transported from, within, and to the geographical area where the chain is located. Then, depending on the market demand, bio-fuels may be used for electric power generation as well as for transportation and process machineries. For instance, in the agro-energy production chain based on sunflower cultivation, one

[1] A promising opportunity seems based on the production of cellulosic bioethanol, which is also called second generation bioethanol (Widenoja, 2007).

ton of bio-fuel is produced by 2.5 tons of sunflower and may be used for transportation and cultivation processes of the same chain.
Suitable locations for the bioelectricity production plant and the bio-fuel conversion plant also provide lower transportation costs for intermediate flows. Biomass transportation can account for about 5% net carbon emissions (Bergman and Zerbe, 2004).
Recent studies (Harris and Adams, 2004; Albino et al., 2007a; Timmons et al., 2007) on bioenergy production chain have shown that plant (including electric generating facility) scale and location have strong economic impact in particular when cultivation areas are highly dispersed. Large scale plant may have high construction costs (e.g. 35 million of euros for 80.000 t/yr biomass capacity), large biomass source area, and then high transportation cost. In some countries, such as Brazil, where the distance matters for transportation there are also small-scale plants that serve each cultivation area. In this case, transportation costs and pollutant emissions caused by transportation are reduced but the investment increases.
Each cultivation area in a region has its specificity such as soil quality, irrigation availability, climate conditions, etc.. A cultivation area may require irrigation because of climate conditions, more fertilizers because of less quantity of minerals in the soil or may need more workforce to cultivate the crop because of poor technology level utilized for cultivation process or of more complex geomorphology of the land. Then, each area has different productivity. Moreover, because of different size, each area produces different levels of outputs (cultivated crop) with different cultivation costs. Productivity and costs are space-related variables.
Depending on the boundaries of the region where the analysis of the agro-energy production chain is limited, a dispersion degree of the cultivation areas may be also defined. Different authors (Borjesson, 1996; Voivontas et al., 2001; Albino et al., 2007b) show that the more dispersed the cultivation areas, the more energy is spent and more pollution is emitted in an agro-energy production chain.
Finally, considering the large amount of materials transferred along the chain in the region, transportation infrastructure is an important asset. Poor availability and quality of such an asset, as is usual in rural areas, may negatively impact the economic performance of the chain. In fact, transportation infrastructure affects cultivation areas, plants, and primary inputs and final market accessibility in terms of how they are easily approached. As a result, different levels of value-added are expected depending on the impact of space-related variables.
In the paper, the spatial analysis of agro-energy production chains is focused on the following main aspects: i) different location, productivity, and size of each area, ii) dispersion degree of the areas, iii) transportation infrastructure, and iv) different accessibility level of each process. The impact of these space-related elements on the performance of agro-energy production chains is investigated using spatial input-output analysis.

3. Spatial Input-Output Analysis and Models

Input-Output (IO) approach has been typically applied to analyse the economic structure of nations and regions, in terms of flows between sectors and firms (Leontief, 1941). The analysis of the interdependences among such entities permits the evaluation of the effect of technological and economic change at regional, national, and international level. The input-output framework of analysis was developed by Wassily Leontief in the late 1920s and early 1930s. Since the beginning, space has been implicitly considered in input-output analysis. In fact, input-output analysis was designed for application at a national (and then geographical) level; subsequent developments have extended it to both the sub-national (regional) and supra-national (global) level (Leontief and Strout, 1963). About these developments an interesting and historical overview is provided by Polenske (2004).
In general, the economic activity of a region can be associated with “n” producing sectors. Input-output accounts attempt to capture the interconnections of an economy by recording, for a given period (say one year), the economic transactions that occur in the economy. These transactions can

be viewed from the point of view of either the selling sector in the region or the buying sector in the region.
In many-regional input-output models the measurement and modeling of the economic interdependencies among the regions are the essential issue. Connected regional input-output models consider all the regions of interest and imports & exports and take into account the relationships with the rest of the world.
In the interregional input-output (IRIO) model, an attempt is made to capture exactly shipments of output from a sector of a region to sectors in other regions.
The important observation to make about these data is that they require both spatial and sectoral information about the origin of an inter-industry transaction and also about the destination.
Data required to link more than just a few regions in a true interregional input-output model can require a huge effort. For this reason, IRIO models containing many regions have seldom been implemented in practice. A model that is designed to overcome some of these data requirements, while retaining the spirit of the IRIO framework, has come to be known as the multiregional input-output (MRIO) model. The simplifying idea here is to make use of transactions data in which the sector of destination is ignored.
More specific experiences with input-output in spatial economics have been performed. Spatial elements can be introduced as complementary to input-output analysis. In particular, the presence of externalities and of topological variables (specified distances, coordinates, densities, etc.) have to be considered in problems such as the economic activity location (see, for instance, Paelinck, 2004) and some metrics are proposed to take into account distances (Kuiper et al., 1990).
According to the different level of analysis, I-O models can be aggregated or disaggregated. Miller and Blair (1985) use a disaggregated level and consider the pattern of materials and energy flows amongst industry sectors, and between industry and consumer industry. A higher level of disaggregation is useful to define a model better fitting real material and energy flows. However, the drawback of working on a high level of disaggregation is represented by the lack of consistency in the input coefficients. In fact, it is sufficient that technological changes happen in a process to modify the input coefficients. On the other hand, because of the small scale, it is easy to know which technological changes occur in one or more processes and the modifications to apply to the technical coefficients.
Enterprise I-O models constitute a particular set of I-O models, useful to complement the managerial and financial accounting systems currently used extensively by firms (Grubbstrom and Tang, 2000; Polenske, 2001; Marangoni and Fezzi, 2002; Marangoni et al., 2004). In particular, Lin and Polenske (1998) proposed a specific I-O model for a steel plant, based on production processes. Similarly, Albino et al. (2002) have developed I-O models for analyzing the complex structure of global and local supply chains, in terms of materials, energy, and pollutants flows.
Enterprise I-O models can be applied to contexts characterized by the geographical dimension, such as in the case of industrial districts (Albino et al., 2003). Enterprise I-O models based on processes have been also adopted to evaluate the effect of different coordination policies of freight flows on the logistics and environmental performance of an industrial district (Albino et al., 2007c).
However, for better addressing the spatial dimension, the I-O approach can be integrated with GIS technology, in order to geographically refer all the inputs and outputs accounted in the models. GIS represents a powerful tool constituted by integrated systems of computer hardware, software, and trained personnel, linking topographic, demographic, utility, facility, image and other resource data geographically referred. GIS can be adopted as a decision support system that enables users to solve problems, organizing and processing information both geographically and logically (Malczewski, 2004). An interesting application of I-O models and GIS technology is reported, for instance, by Zhan et al. (2005), who develop a framework for the evaluation of the main causal factors affecting the occurrence of yellow-dust storms in China. A similar integration is proposed by Van der Veen and Logtmeijer (2003) to evaluate the vulnerability of a geographical area for flooding.
Enterprise I-O models integrated with GIS technology have been also developed for logistics (Albino et al., 2007a) and bioenergy (Albino et al., 2007b) system analysis.

4. The Input-Output Model

An agro-energy production chain is composed by the network of production processes, which transform a part of the crops into energy resources. This network can be fully described if all the interrelated processes as well as input and output flows are identified. In particular, different types of production process are distinguished, namely fertilizers production, seeds preparation, cultivation, food processing (since, in general, a part of the crops produced can be also destined to the food industry), oil conversion, biodiesel production, electric energy production, and transportation.
Let us consider the chain processes reported in Figure 1, where all the inputs and outputs required for each process are indicated. Wastes, primary inputs, and by-products are also reported, referring to the specific case of sunflowers.

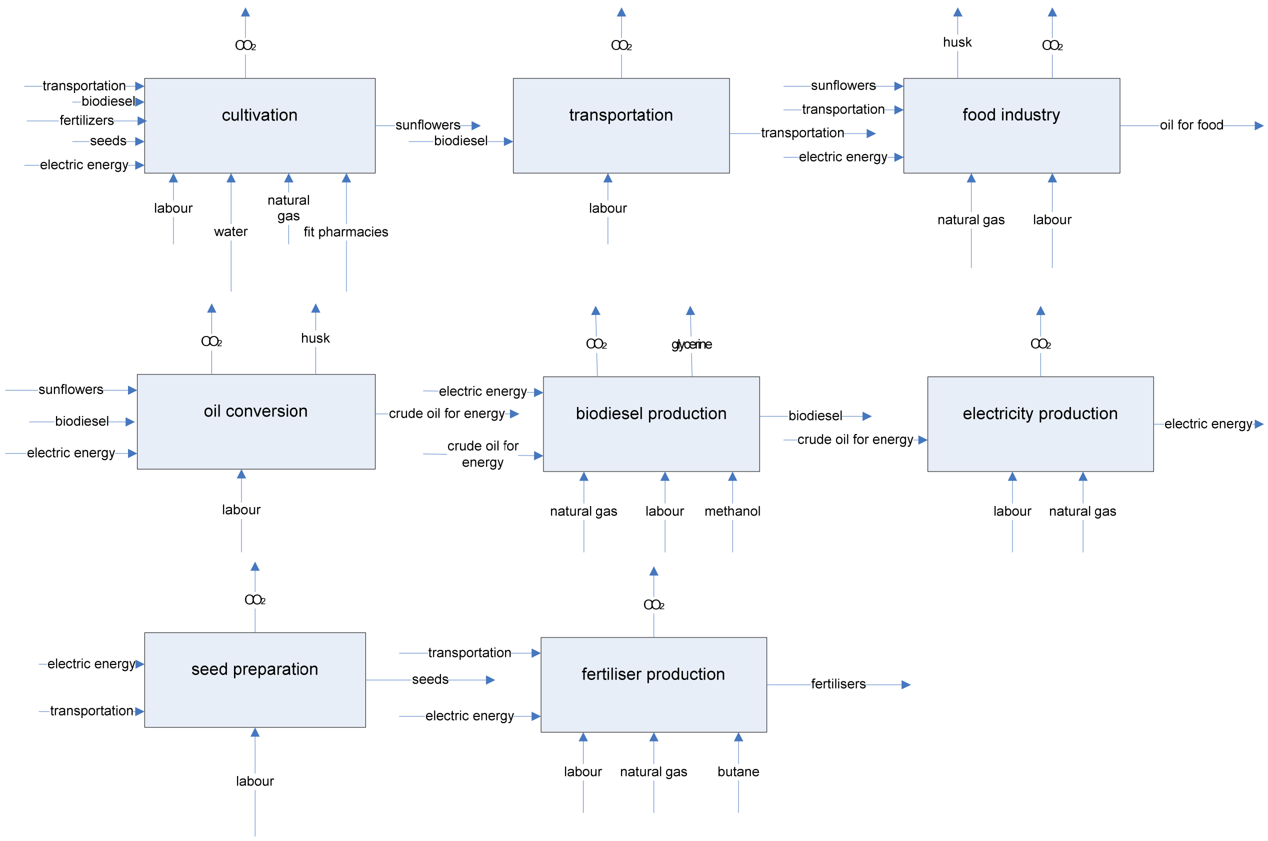


Figure 1. All the inputs and outputs required for each production process.

The enterprise I-O model is then formalized as follows. Let $\boldsymbol{Z}_0$ be the matrix of domestic (i.e. to and from production processes within the supply chain) intermediate deliveries, $\boldsymbol{f}_0$ is the vector of final demands, and $\boldsymbol{x}_0$ the vector of gross outputs.
If n processes are considered, the matrix $\boldsymbol{Z}_0$ is of size n x n, and the vectors $\boldsymbol{f}_0$ and $\boldsymbol{x}_0$ are n x 1. It is assumed that each process has a single main product as its output. Each of these processes may require intermediate inputs from the other processes, but not from itself so that the entries on the main diagonal of the matrix $\boldsymbol{Z}_0$ are zero.
The main product of transportation is the distance covered by the transportation means to convey all main products to their destinations (backward trips are also considered). Moreover, for a more detailed analysis, the transportation process T can be distinguished into h processes (θ_k , k=1,…, h), corresponding to the h tracks covered by transportation means to deliver products. In this case, the main product of each track is measured as the distance covered by transportation vehicle..

Of course, also other inputs are required for the production. These are *s* primary inputs (i.e. products not produced by one of the *n* production processes). Next to the output of the main product, the processes also produce *m* by-products and wastes. $\boldsymbol{r}_0$ and $\boldsymbol{w}_0$ are the primary input vector, and the by-product and waste vector of size *s* x 1 and *m* x 1, respectively.
Define the intermediate coefficient matrix $\boldsymbol{A}$ as follows:

$$\boldsymbol{A} = \boldsymbol{Z}_0 \hat{\boldsymbol{x}}_0^{-1} \tag{1}$$

where a "hat" is used to denote a diagonal matrix. We now have:

$$\boldsymbol{x}_0 = \boldsymbol{A}\boldsymbol{x}_0 + \boldsymbol{f}_0 = (\boldsymbol{I} - \boldsymbol{A})^{-1} \boldsymbol{f}_0 \tag{2}$$

It is possible to estimate $\boldsymbol{R}$, the *s* x *n* matrix of primary input coefficients with element r_{kj} denoting the use of primary input *k* (1,…, s) per unit of output of process *j*, and *W*, the *m* x *n* matrix of its output coefficients with element w_{kj} denoting the output of by-product or waste type *k* (1,…, m) per unit of output of process *j*. It results:

$$\boldsymbol{r}_0 = \boldsymbol{R}\boldsymbol{x}_0 \tag{3}$$

$$\boldsymbol{w}_0 = \boldsymbol{W}\boldsymbol{x}_0 \tag{4}$$

Note that the coefficient matrices $\boldsymbol{A}$, $\boldsymbol{R}$, and $\boldsymbol{W}$ are numerically obtained from observed data. A change in the final demand vector induces a change in the gross outputs and subsequently changes in the input of transportation, primary products, and changes in the output of by-products and waste. Suppose that the final demand changes into $\bar{\boldsymbol{f}}$, and that the intermediate coefficients matrix $\boldsymbol{A}$, the primary input coefficients matrix $\boldsymbol{R}$, and the output coefficients matrix $\boldsymbol{W}$, are constant (which seems a reasonable assumption in the short-run), then the output changes into:

$$\bar{\boldsymbol{x}} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \bar{\boldsymbol{f}} \tag{5}$$

Given this new output vector, the requirements of primary inputs and the outputs of by-product and waste are:

$$\bar{\boldsymbol{r}} = \boldsymbol{R}\bar{\boldsymbol{x}} \tag{6}$$

$$\bar{\boldsymbol{w}} = \boldsymbol{W}\bar{\boldsymbol{x}} \tag{7}$$

where $\bar{\boldsymbol{r}}$ gives the new *s* x 1 vector of primary inputs, and $\bar{\boldsymbol{w}}$ the new *m* x 1 vector of by-products and waste types.
The enterprise I-O model can be also adopted to account the monetary value associated with each production process. In particular, let $\boldsymbol{p}_0$ be the vector of the prices with element p_i denoting the unitary price of the main product at the end of the process *i* (no downstream transportation is included). Thus, considering the vector of the gross outputs $\boldsymbol{x}_0$, we can compute the vector $\boldsymbol{y}_0$, representing the total revenues associated with each gross output as follows:

$$\boldsymbol{y}_0 = \hat{\boldsymbol{x}}_0 \boldsymbol{p}_0 \tag{8}$$

Moreover, we can define the matrix $\boldsymbol{B}$, where the generic element b_{ij} is expressed as:

$$\boldsymbol{b}_{ij} = \boldsymbol{a}_{ij} \frac{\boldsymbol{p}_i}{\boldsymbol{p}_j} \tag{9}$$

Then, we have:

$$\boldsymbol{y}_0 = \boldsymbol{B}\boldsymbol{y}_0 + \hat{\boldsymbol{f}}_0 \boldsymbol{p}_0 = (\boldsymbol{I} - \boldsymbol{B})^{-1} \hat{\boldsymbol{f}}_0 \boldsymbol{p}_0 \tag{10}$$

If *n* production processes are considered, the matrix $\boldsymbol{B}$ is of size *n* x *n*, and the vectors $\hat{\boldsymbol{f}}_0 \boldsymbol{p}_0$ and $\boldsymbol{y}_0$ are *n* x 1. Moreover, we can define the vector of the prices $\boldsymbol{p}_0^w$ which is a *m* x 1 vector, where p_i^w represents the unitary price associated to the wastes and by-products for all processes. In particular, wastes and by-products will have non-positive and non-negative price, respectively. Hence, considering the matrix $\boldsymbol{W}$, we can identify the vector $\boldsymbol{y}_0^w$, a *n* x 1 vector, representing the total revenues associated with all wastes and by-products for each process as follows:

$$\boldsymbol{y}_0^w = \left[(\boldsymbol{p}_0^w)^T \boldsymbol{W}\hat{\boldsymbol{x}}_0\right]^T \tag{11}$$

Of course, also costs are sustained in the production chain. Let $\boldsymbol{y}_0^r$ which is a *n* x 1 vector, be the vector of the costs associated to each process for the primary inputs, including wages and salaries, and $\boldsymbol{d}_0$ which is a n x 1 vector for investments amortization (observed data). For the accounting of all types of primary inputs the vector $\boldsymbol{p}_0^r$ which is a *s x* 1 vector, is also defined in order to calculate $\boldsymbol{y}_0^r$.The vector of intermediate inputs costs, $\boldsymbol{y}_0^z$ which is a *n* x 1 vector, is also calculated using $\hat{\boldsymbol{p}}_0$ and $\boldsymbol{i}$ (*n* x 1 unit vector, having all elements equal to one). They result:

$$\boldsymbol{y}_0^r = \left[(\boldsymbol{p}_0^r)^T \boldsymbol{R}\hat{\boldsymbol{x}}_0\right]^T \tag{12}$$

$$\boldsymbol{y}_0^z = \left[(\boldsymbol{i})^T \hat{\boldsymbol{p}}_0 \boldsymbol{A}\hat{\boldsymbol{x}}_0\right]^T \tag{13}$$

Then, the profit of the whole production chain ( ) can be computed as:

$$= \sum_{i=1}^{n} (\boldsymbol{y}_i + \boldsymbol{y}_i^w - \boldsymbol{y}_i^z - \boldsymbol{y}_i^r - \boldsymbol{d}_i) \tag{14}$$

A change in final demand, as mentioned above, will cause a change into:

$$\bar{\boldsymbol{y}} = \hat{\bar{\boldsymbol{x}}}\, \boldsymbol{p}_0 \tag{15}$$

$$\bar{\boldsymbol{y}}^w = \left[(\boldsymbol{p}_0^w)^T \boldsymbol{W}\hat{\bar{\boldsymbol{x}}}\right]^T \tag{16}$$

$$\bar{\boldsymbol{y}}^r = \left[(\boldsymbol{p}_0^r)^T \boldsymbol{R}\hat{\bar{\boldsymbol{x}}}\right]^T \tag{17}$$

$$\bar{\boldsymbol{y}}^z = \left[(\boldsymbol{i})^T \hat{\boldsymbol{p}}_0 \boldsymbol{A}\hat{\bar{\boldsymbol{x}}}\right]^T \tag{18}$$

These values permit the evaluation of the economic performance which represents the expected result for all the actors involved in the production chain.

5. Theoretical Case Example

In this section, some spatial variables are included in the proposed I-O model to analyse their impact on the economic and environmental performance of a simple and theoretical agro-energy production chain. In particular, the size of the cultivation areas, their dispersion degree, and the transport infrastructure accessibility are considered. All the production processes are characterised by geographical information about their location. All the processes and the related geographical areas represent the geographical system of the agro-energy production chain. In particular, let's assume that the chain refers to sunflowers and it is composed by eight types of production process (i.e. fertilizers production, seed production, sunflower cultivation, food processing, oil conversion, biodiesel production, electric energy production, and transportation) and all products are delivered adopting trucks with load capacities equal to 5 t.

Let us assume that the process of cultivation is composed by eight distinct processes. On the contrary, fertilizers production, seeds preparation, food processing, oil conversion, biodiesel production, electric energy production, and transportation are each represented by only one process. Moreover, six primary inputs are taken into account, namely workforce (r_1), water (r_2), butane (r_3), natural gas (r_4), methanol (r_5), and fit pharmacy (r_6). For the sake of simplicity, for these inputs transportation is not considered. Finally, three wastes and by products are considered: CO_2 (w_1), glycerine (w_2), and husk (w_3). In Table 1 the production processes are listed.

All the processes are located according to a radial model. In particular, cultivation processes are distributed along the circle line, while fertilizers production, seed preparation, food processing, oil conversion, biodiesel production, and electric energy production are located at the centre of the circle. Finally, the eight distinct tracks (θ_1, θ_2, …, and θ_8) of road are shown (Figure 2), but the aggregated transportation process T is considered in the model.

Production processes	Type
p_1	Cultivation
p_2	Cultivation
…	…
p_8	Cultivation
p_9	Fertilizers production
p_{10}	Seeds preparation
p_{11}	Food processing
p_{12}	Oil conversion
p_{13}	Biodiesel production
p_{14}	Electric energy production
T	Transportation

Table 1. Production processes.

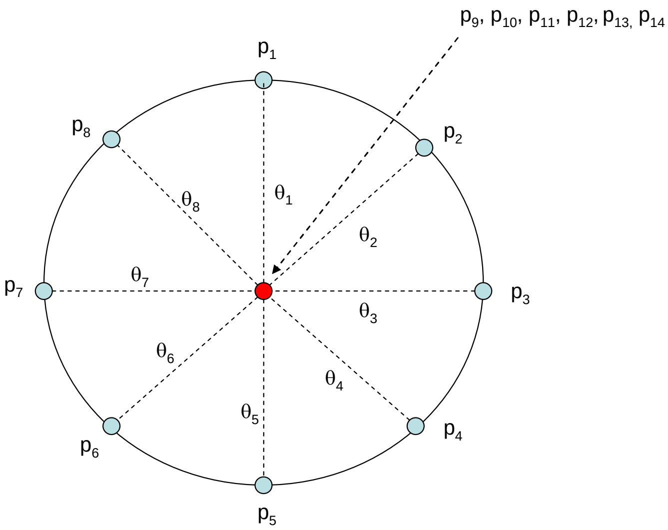


Figure 2. Location of processes.

In Table 2 the physical balance table referred to the agro-energy production chain is reported.
The economic and environmental performance of the production chain is analysed taking into account seven different measures, i.e.: i) the total quantity of oil for food produced (x_{11}); ii) the total quantity of oil for energy produced (x_{12}); iii) the total quantity of biodiesel produced (x_{13}); iv) the total quantity of electric energy produced (x_{14}); v) the profit of the whole agro-energy production chain ( ); vi) the total workforce, in terms of hours of labour (r_1); vii) the total emissions of CO_2 (w_{CO_2}). In particular, CO_2 emissions per unit of main product caused by each production process are reported in Table 3.

Process	CO_2 emissions
Biodiesel production	358,2 [kg/ton]
Cultivation	451,6 [kg/ha]
Electric energy production	1,56 [kg/MWh]
Fertilizers production	689 [kg/ton]
Food processing	58,3 [kg/ton]
Oil conversion	52,6 [kg/ton]
Seeds preparation	174,3 [kg/ton]
Transportation	0,28 [kg/km]

Table 3. CO_2 emissions per unit of main product.

Process	units	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	p_{13}	p_{14}	T	i_0	e_0	f_0	x_0
p_1	[t]											$z_{1,11}$	$z_{1,12}$							x_1
p_2	[t]											$z_{2,11}$	$z_{2,12}$							x_2
p_3	[t]											$z_{3,11}$	$z_{3,12}$							x_3
p_4	[t]											$z_{4,11}$	$z_{4,12}$							x_4
p_5	[t]											$z_{5,11}$	$z_{5,12}$							x_5
p_6	[t]											$z_{6,11}$	$z_{6,12}$							x_6
p_7	[t]											$z_{7,11}$	$z_{7,12}$							x_7
p_8	[t]											$z_{8,11}$	$z_{8,12}$							x_8
p_9	[t]	$z_{9,1}$	$z_{9,2}$	$z_{9,3}$	$z_{9,4}$	$z_{9,5}$	$z_{9,6}$	$z_{9,7}$	$z_{9,8}$											x_9
p_{10}	[t]	$z_{10,1}$	$z_{10,2}$	$z_{10,3}$	$z_{10,4}$	$z_{10,5}$	$z_{10,6}$	$z_{10,7}$	$z_{10,8}$											x_{10}
p_{11}	[t]																i_{11}	e_{11}	f_{11}	x_{11}
p_{12}	[t]													$z_{12,13}$	$z_{12,14}$					x_{12}
p_{13}	[t]												$z_{13,12}$			$z_{13,T}$	i_{13}	e_{13}	f_{13}	x_{13}
p_{14}	[MWh]	$z_{14,1}$	$z_{14,2}$	$z_{14,3}$	$z_{14,4}$	$z_{14,5}$	$z_{14,6}$	$z_{14,7}$	$z_{14,8}$	$z_{14,9}$	$z_{14,10}$	$z_{14,11}$	$z_{14,12}$				i_{14}	e_{14}	f_{14}	x_{14}
T	[km]	$z_{T,1}$	$z_{T,2}$	$z_{T,3}$	$z_{T,4}$	$z_{T,5}$	$z_{T,6}$	$z_{T,7}$	$z_{T,8}$	$z_{T,9}$	$z_{T,10}$	$z_{T,11}$								x_T
Primary inputs																				
r_1	[hours]	$r_{1,1}x_1$	$r_{1,2}x_2$	$r_{1,3}x_3$	$r_{1,4}x_4$	$r_{1,5}x_5$	$r_{1,6}x_6$	$r_{1,7}x_7$	$r_{1,8}x_8$	$r_{1,9}x_9$	$r_{1,10}x_{10}$	$r_{1,11}x_{11}$	$r_{1,12}x_{12}$	$r_{1,13}x_{13}$	$r_{1,14}x_{14}$	$r_{1,T}x_T$				
r_2	$[m^3]*10^3$	$r_{2,1}x_1$	$r_{2,2}x_2$	$r_{2,3}x_3$	$r_{2,4}x_4$	$r_{2,5}x_5$	$r_{2,6}x_6$	$r_{2,7}x_7$	$r_{2,8}x_8$											
r_3	[kg]									$r_{3,9}x_9$										
r_4	$[m^3]$	$r_{4,1}x_1$	$r_{4,2}x_2$	$r_{4,3}x_3$	$r_{4,4}x_4$	$r_{4,5}x_5$	$r_{4,6}x_6$	$r_{4,7}x_7$	$r_{4,8}x_8$	$r_{4,9}x_9$		$r_{4,11}x_{11}$		$r_{4,13}x_{13}$	$r_{4,14}x_{14}$					
r_5	[t]													$r_{5,13}x_{13}$						
r_6	[t]	$r_{6,1}x_1$	$r_{6,2}x_2$	$r_{6,3}x_3$	$r_{6,4}x_4$	$r_{6,5}x_5$	$r_{6,6}x_6$	$r_{6,7}x_7$	$r_{6,8}x_8$											
Wastes and by-products																				
w_1	kg	$w_{1,1}x_1$	$w_{1,2}x_2$	$w_{1,3}x_3$	$w_{1,4}x_4$	$w_{1,5}x_5$	$w_{1,6}x_6$	$w_{1,7}x_7$	$w_{1,8}x_8$	$w_{1,9}x_9$	$w_{1,10}x_{10}$	$w_{1,11}x_{11}$	$w_{1,12}x_{12}$	$w_{1,13}x_{13}$	$w_{1,14}x_{14}$	$w_{1,T}x_T$				
w_2	[t]													$w_{2,13}x_{13}$						
w_3	[t]											$w_{3,11}x_{11}$	$w_{3,12}x_{12}$							

Table 2. Physical I-O balance table.

Two distinct coefficients, α and β, are used to distinguish the amount of crop destined to food processing or energy production, and the amount of extracted oil destined to biodiesel (x_{13}) or electric energy (x_{14}) produced, respectively. In particular, it results:

$$\sum_{i=1}^{8} z_{i,11} = \alpha \cdot \sum_{i=1}^{8} x_i \;;\; \sum_{i=1}^{8} z_{i,12} = (1-\alpha) \cdot \sum_{i=1}^{8} x_i \tag{19}$$

$$z_{12,13} = \beta \cdot x_{12} \;;\; z_{12,14} = (1-\beta) \cdot x_{12} \tag{20}$$

Three different analyses are performed, namely “size analysis”, “dispersion analysis”, and “accessibility analysis”. In particular, in the first and second analysis the production capability of the cultivation processes, in terms of size of the cultivation areas, and their distance from the other production processes are investigated, respectively. In the third analysis, the accessibility is modelled in terms of the average truck speed and, then, the transportation cost is evaluated.
In all the cases, referred to the period of one year, the coefficients α and β are defined in order to assure the energy balance of the whole chain, i.e. all the electric energy and fuel required by the production processes are produced within the production chain.
In Table 4 the unitary price of the main products relevant for the analysis (i.e. sunflowers harvest, oil for food, biodiesel, and electric energy) is reported. In particular, the price of sunflowers harvest and of oil for food is the average over all prices estimated assuming revenue equal to total cost plus a fixed percentage of profit, for each process.

Product	**Unit**	**Price**
Sunflowers harvest	[€/kg]	0,35
Oil for food	[€/kg]	1,06
Biodiesel	[€/kg]	1,25
Electric energy	[€/MWh]	120

Table 4. Unitary prices of main products.

For the sake of brevity data and computations are not included in the paper, but they can be available if requested to the authors.

5.1. Size Analysis

Let us assume three different scenarios, being the land cropped with sunflowers equal to 5, 10, and 20 thousands hectares, respectively. In each scenario, the radius of the geographic system and, hence, the distance between the cultivation and the other processes is equal to 60 km. Finally, the accessibility is constant, being the average trucks speed equal to 50 km/h. In Table 5 the economic and environmental performance measures are reported for each scenario.

Performance	**Size [x10^3 ha]**		
	5	**10**	**20**
x_{11} [t]	2.320	4.639	9.278
x_{12} [t]	2.752	5.304	11.008
x_{13} [t]	102	203	407
x_{14} [MWh]	10.465	20.929	41.858
[€]	485.400	970.800	1.941.600
r_1 [h]	333.724	667.448	1.334.895
w_{CO_2} [t]	4.360	8.721	17.441

Table 5. Economic and environmental performance in the size analysis.

As expected, the size of the cultivated land positively affects the production of oil for food (x_{11}), bio-fuel (x_{13}), and electric energy (x_{14}). Consequently, the profit of the whole chain, and the workforce requirement notably raise. However, the total amount of CO_2 emitted increases, being the above mentioned production processes characterised by a high degree of pollution rate. Hence, a trade-off between the economic and environmental performance has to be reached.

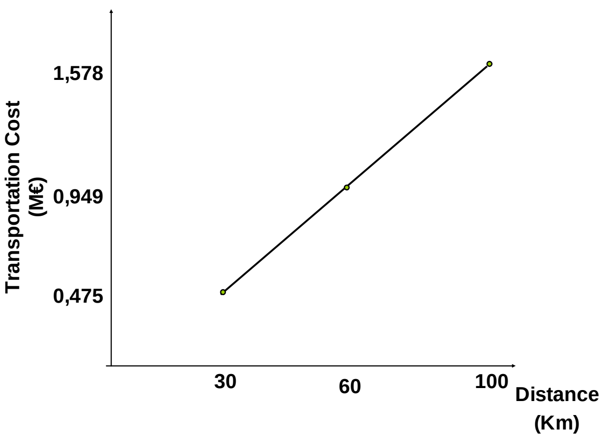
5.2. Dispersion Analysis

In this analysis the size of the cropped land and the average trucks speed are assumed to be constant and equal to 10 thousands hectares and 50 km/h, respectively. On the contrary, in order to analyse the dispersion degree of the area, the distance between the cultivation and the other processes assumes three different values: 30 km, 60 km, and 100 km. Table 6 shows the economic and environmental performance for each distance.

Performance	**Distance [km]**		
	30	**60**	**100**
x_{11} [t]	4.716	4.639	4.537
x_{12} [t]	5.421	5.504	5.614
x_{13} [t]	130,4	203,5	300
x_{14} [MWh]	20.930	20.929	20.929
[€]	1.293.908	970.800	541.489
r_1 [h]	659.629	667.446	677.836
w_{CO_2} [t]	8.584	8.721	8.902

Table 6. Economic and environmental performance in the dispersion analysis.

As the distance increases, higher amount of biodiesel is produced, and the total quantity of sunflower oil for food decreases. It depends on the dispersion degree, which entails a greater consumption of fuel by the transportation process. Then, in order to assure the energetic balance of the system, a greater quantity of sunflower oil has to be supplied to the agro-energy production, especially to the biodiesel one. In other words, as the dispersion degree increases, the coefficients α and β have to assume lower and higher values, respectively.
Regarding the profit of the system, it decreases because of the higher dispersion degree and transportation costs (Figure 3). Finally, the dispersion degree negatively affects the environmental performance of the system, since the increasing amount of CO_2 emitted by the transportation process.
The trends of the profit and of CO_2 emissions are reported in Figure 4 and 5, respectively.



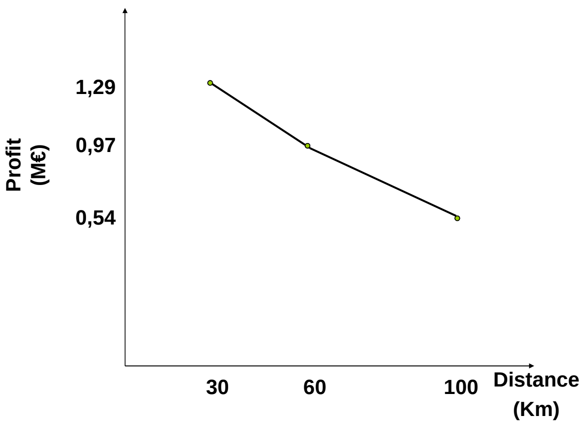
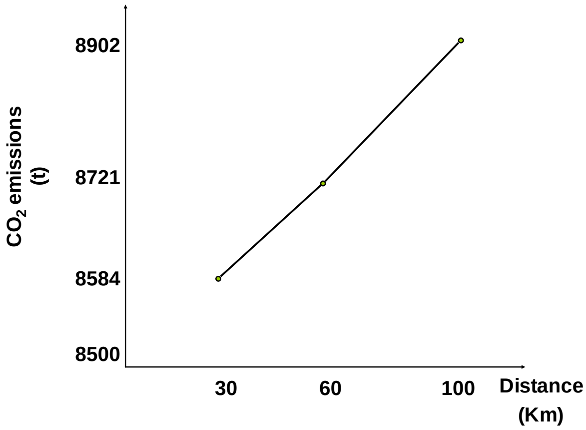


Figure 3. Transportation cost in the dispersion analysis. Figure 4. Profit in the dispersion analysis.



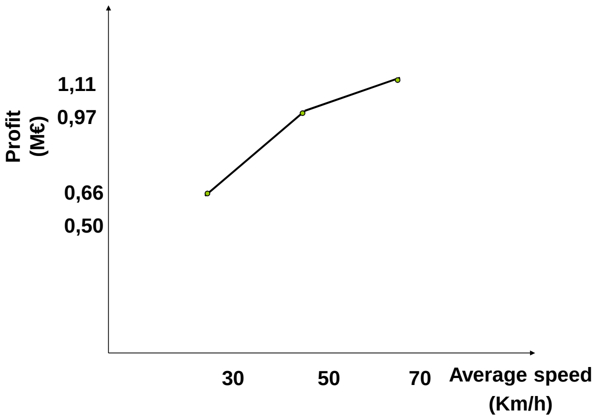


Figure 5. CO_2 emissions in the dispersion analysis. *Figure 6. Profit in the accessibility analysis.*

5.3. Accessibility Analysis

In this case the accessibility is analysed in terms of quality of transportation infrastructure. With this regard, the average trucks speed changes, assuming values 30, 50, and 70 km/h. The size of the cropped land is assumed to be 10 thousands hectares and the distance between the cultivation and the other processes is equal to 60 km.
In Table 7 the values of the economic and environmental performance measures are provided.

Performance	**Accessibility [km/h]**		
	30	**50**	**70**
x_{11} [t]	4.639	4.639	4.639
x_{12} [t]	5.504	5.504	5.504
x_{13} [t]	203	203	203
x_{14} [MWh]	20.929	20.929	20.929
[€]	655.509	970.800	1.105.925
r_1 [h]	677.993	667.448	662.928
w_{CO_2} [t]	8.721	8.721	8.721

Table 7. Economic and environmental performance in the accessibility analysis.

As shown in Table 7, the accessibility only affects the profit and the workforce requirement of the system. In particular, the profit increases, since a reduction of the transportation costs due to the higher quality of transportation infrastructure. Regarding the workforce requirement, it diminishes because less time is required to convey products from origins to destinations, and, hence, a lower quantity of workers has to be hired by the transportation process. The relationship between profit and accessibility is depicted in Figure 6.

Figure 7 shows the negative relationship between the transportation infrastructure accessibility and the transportation cost of the whole chain. This result confirms the importance of efficient infrastructures for improving the efficiency of cultivation and food production processes.

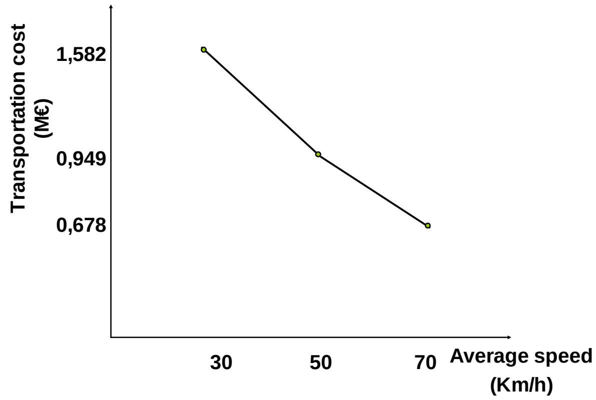


Figure 7. Transportation cost in the accessibility analysis.

5.4. Energy-unbalanced chains

In this section extreme values of α and β are considered and four theoretical cases are compared: food-oriented (α=1), biodiesel-oriented (α=0, β=1), bioelectricity-oriented (α=0, β=0), and energy-balanced production chains. In the food-oriented chain, all yield is dedicated to produce food and fossil energy is used to sustain all processes. In the biodiesel-oriented chain the system gives excess biodiesel to final demand, uses non-renewable electric energy, and imports food. To compare cases, for the sake of simplicity, the amount of food to be imported is equal to the food produced in the energy-balanced chain. Finally, in the bioelectricity-oriented production chain, the system sells the excess electricity, imports (for the same amount of the energy-balanced chain case) food, and uses fossil fuel to sustain itself. The results are represented in Table 8 where r_7, r_8, and r_9 denote the imported food, diesel oil, and non-renewable electricity, respectively. In all cases, the total cultivation area size, the distance between production units and each cultivation area, and the truck velocity are considered equal to 10.000 ha, 60 km, and 50 km/h, respectively. So, the impacts of spatial variables are neglected.

Performance	**Food-oriented chain** (α=1)	**Biodiesel-oriented chain** (α=0, β=1)	**Bioelectricity-oriented chain** (α=0, β=0)	**Energy-balanced chain**
x_{11} [t]	9.750	0	0	4.639
x_{12} [t]	0	10.500	10.500	5.504
x_{13} [t]	0	9.188	0	203
x_{14} [MWh]	0	0	41.685	20.926
[€]	4.051.046	4.546.234	-2.161.059	970.800
r_1 [h]	614.499	603.797	718.534	667.446
r_4 [m^3]	1.998.925	3.757.500	1.966.375	2.021.485
r_7 [t]	0	4.639	4.639	0
r_8 [l]	173.105	0	314.840	0
r_9 [MWh]	20.924	21.196	0	0
w_{CO_2} [kg]	5.366.136	7.637.048	9.159.278	8.720.673

Table 8. Economic and environmental performance in the four cases.

As shown in Table 8, the total profit of the system is negative in the bioelectricity-oriented chain. In fact, it is not convenient (without any subsidies) to produce bioelectricity instead of other main products. As a consequence, this causes low profits in the energy-balanced chain. The highest total

profit is obtained for the biodiesel-oriented chain also because diesel oil is more expensive than biodiesel. High profit in biodiesel-oriented chain is also due to the sale of the glycerine (by-product).
On the other hand, the highest workforce is required by the bioelectricity-oriented chain and, because of the automation level adopted in biodiesel production, less workforce is required in biodiesel-oriented chain.
In terms of CO_2 emissions, since in biodiesel- and food-oriented chains the electricity is not produced in the system but imported, the bioelectricity-oriented chain is less convenient than the food- and biodiesel-oriented chains. Since in the biodiesel-oriented chain, biodiesel production uses more energy than food production (and consequently emits more CO_2), food-oriented chain is more convenient in terms of CO_2 emissions. In the case of energy-balanced chain, the system causes more CO_2 emissions with respect to biodiesel- and food-oriented chains.
In the biodiesel- and bioelectricity-oriented chains, the same amount of food produced in the system in the case of energy-balanced chain is imported. Such an assumption is adopted being the energy-balanced chain considered self-sustained in terms of food and energy needs. This import of food (which is a main product) is accounted, for the sake of simplicity, as a primary input (r_7)

6. A Case Study

In this section, an actual case study related to the development of an agro-energy production chain, is provided. The aim is to evaluate the economic and environmental performance of the chain and how it is affected by specific chain characteristics. The case study regards the geographical area of Puglia, a region located in the south east of Italy. Puglia covers an area of 19.362,90 square km with 4.068.167 inhabitants. In particular, 1,5% of the surface is constituted by mountain, 45,3% by hill, and 53,2% by plain. Agriculture represents an important economic activity for the region, with a cropped land of 1.379.278 ha. Different crops are present in Puglia, such as sunflower, colza, soybean, sugar beet, green corn, wheat, and tobacco.
The actual production chain concerns the production of biodiesel and electric energy from the sunflower oil. 130 cultivation processes, covering an area of 10.546,88 ha, are considered. In particular, these processes are located in the municipalities of Foggia, Brindisi, and Lecce.
The plants of oil conversion, biodiesel production, and electric energy production are all located in the same place (in the area of Bari) (scenario A). Moreover, for the sake of simplicity, also the production of seeds, fertilizers, and the food processing are assumed to be set in the same place.
Each hectare of land cropped with sunflowers is assumed to produce 2,5 tons of sunflower seeds and 1,1 tons of vegetal oil. Also in this case, all products are delivered adopting trucks with load capacities equal to 5 t. Finally, the average trucks speed in the considered area is 50 km/h. The values of α and β are set to assure the energy balance of the production chain.
A different location of the production plants (i.e. oil conversion, bio-fuel production, electric energy production) can be examined to compare economic and environmental performance.
With this regard, we assume that the plant can be located nearer to the cropped lands characterised by the greatest sizes (in the municipality of Foggia) (scenario B). Under this assumption, the economic and environmental performance of the two scenarios are evaluated and compared. Main results are shown in Table 9.

Performance	Scenario A	Scenario B
x_{11} [t]	4.691	4.750
x_{12} [t]	6.022	5.958
x_{13} [t]	402	347
x_{14} [MWh]	22.082	22.080
[€]	125.553	379.848
r_1 [h]	724.279	718.255
w_{CO_2} [t]	9.553	9.448

Table 9. Economic and environmental performance in scenario A and B.

Data reveal that the profit increases moving from the scenario A (plants located in the centre of the geographic system) to B (plants located nearer the largest areas), because of the decrease of transportation costs. Thus, this means that locating the plants nearer to the largest area (Foggia) causes an increase of the system’s profit. Moreover, this choice implies the reduction of CO_2 emitted with a consequent improvement of the environmental performance. Finally, moving from scenario A to scenario B the less transportation workforce requirement entails the reduction of the workforce level. In particular, the profit increases 200% whereas the CO_2 emissions and the workforce requirement decrease 1% and 0,8%, respectively.
As previously stated, the dispersion degree and the size of each cultivation process can significantly affect the economic and environmental performance of the chain. For the sake of simplicity, all the different cultivation processes are aggregated for municipality (i.e. Foggia, Brindisi, and Lecce). Assuming the dispersion degree of each municipality as the distance between it and the production plants (municipality of Bari), as the dispersion degree of the municipality increases the corresponding economic and environmental performance decrease (Table 10). For instance the dispersion degree of Foggia is 30% greater than that of Brindisi whereas the profit per hectare for Brindisi is 300% higher than that for Foggia. Due to the highest dispersion degree, Lecce has a loss of 9 €/ha. However, for each municipality the global effect has to be evaluated taking into account the size of the related cultivation areas.

Municipality	**Profit [€/ha]**	**CO_2 emissions [kg/ha]**	**Size [ha]**	**Distance from the production plant [km]**
Brindisi	48	891	1.702	101
Foggia	11	906	6.049	135
Lecce	-9	914	2.795	153

Table 10. Economic and environmental performance of the cultivation areas for each municipality.

Finally, for scenario A the energy-balanced chain is compared with the food-, biodisesel-, and bioelectricity-oriented chains (Table 11).

Performance	**Food-oriented chain** (α=1)	**Biodiesel-oriented chain** (α=0, β=1)	**Bioelectricity-oriented chain** (α=0, β=0)	**Energy-balanced chain**
x_{11} [t]	10.283	0	0	4.691
x_{12} [t]	0	11.074	11.074	6.022
x_{13} [t]	0	9.690	0	403
x_{14} [Mwh]	0	0	44.258	22.082
[€]	3.223.532	3.981.887	-3.116.303	830.647
r_1 [h]	673.003	655.533	776.544	724.279
r_4 [m^3]	2.108.216	3.962.990	1.731.248	2.167.971
r_7 [t]	0	4.691	4.691	0
r_8 [l]	384.192	0	397.829	0
r_9 [MWh]	22.066	22.366	0	0
w_{CO_2} [kg]	5.955.718	8.316.729	10.317.299	9.552.632

Table 11. Economic and environmental performance in all cases for scenario A.

As in the theoretical case, in the bioelectricity-oriented chain the system results in loss. On the other hand, it creates the highest job opportunity. However, bioelectricity-oriented chain causes more CO_2 emissions with respect to the food- and biodiesel-oriented chains due to electricity imports. In the food-oriented chain, lower CO_2 emissions are observed.
The biodiesel-oriented chain gains the highest profit as in the theoretical case due to less energy costs and more by-product income (i.e. glycerine) with respect to the food-oriented chain. In the biodiesel-oriented chain, the highest natural gas consumption is due to the energy need of the biodiesel production process.
Main performance measures for each municipality are reported in Table 12.

Municipality			**Food-oriented chain** (α=1)		**Biodiesel-oriented chain** (α=0, β=1)		**Bioelectricity-oriented chain** (α=0, β=0)		**Energy-balanced chain**	
	Size [ha]	**Distance from the production plant [km]**	**Profit [€/ha]**	**CO_2 emissions [kg/ha]**	**Profit [€/ha]**	**CO_2 emissions [kg/ha]**	**Profit [€/ha]**	**CO_2 emissions [kg/ha]**	**Profit [€/ha]**	**CO_2 emissions [kg/ha]**
Brindisi	1.702	101	348	532	411	777	-261	950	47	891
Foggia	6.049	135	305	564	377	789	-296	979	11	906
Lecce	2.795	153	282	585	359	795	-315	994	-9	914

Table 12. Economic and environmental performance for each municipality in all cases.

Due to the higher dispersion degree, in the municipality of Lecce a lower profit and a higher CO_2 emissions per hectare are observed for all cases. This comparison shows that the dispersion degree may have an important impact on the economic and environmental performance of the chains. This suggests that the economic and environmental performance of an agro-energy production chain can be significantly affected by the spatial characteristics of the processes (the localization of plants, the dispersion and the size of cultivation areas) as well as by the choice of the output mix.

7. Conclusions

The paper analyses the economic and environmental performance of an agro-energy production chain and how spatial variables, such as the size of cultivated areas, their dispersion degree, and the transportation infrastructure accessibility, and the choice of output mix can affect it. With this regard, enterprise I-O models based on processes have been developed. In particular, eight main types of production processes have been considered: cultivation, fertilizers production, seeds production, food processing, oil conversion, biodiesel production, electric energy production, and transportation. Each process is geo-referred.
Three theoretical case examples have been considered referring to the sunflowers cultivation. Results are obtained for an energy-balanced chain and reveal some interesting findings. First, they show how the size of the cultivated areas positively affects the economic performance, in terms of profit and employment, and negatively the environmental one, in terms of CO_2 emitted. Then, the trade-off among these performance measures has to be evaluated.
Second, the dispersion degree has a negative impact on the production chain’s profit, since the increasing costs generated by the transportation process. Regarding the environmental performance, the increased distance between the cultivated areas and the production plants entails a greater quantity of pollutant emissions.
Third, the transportation infrastructure accessibility has a positive effect on the profit of the whole chain, because improving infrastructure (higher accessibility) results in a more efficient transportation. As a consequence, a reduction of workforce for transportation is determined.
The EIO model has been applied to an actual case study to investigate the location of production plants and the dispersion of cultivation areas. In particular, a new possible location is compared

with the actual one. As the plants move from the middle of the geographic system (actual location) to the new location (close to the greatest areas of cultivation), the economic and environmental performance of the system increase. Then, results permit a more in-depth and aware decision-making process. A specific analysis is then performed referring to the dispersion degree characterising cultivation areas for each municipality. A change in the degree differently affects performance measures.
Finally, for both theoretical and actual case studies the chains with different output mix are analyzed and compared. The choice about the output mix has a significant impact on the economic and environmental performance. Then, spatial variables and output mix have to be carefully evaluated in the design and management of an agro-energy production chain.
Further researches should explore other model assumptions in terms of price setting, energy resource utilisation, and boundaries of the system. Moreover significant modelling improvements could be achieved through the adoption of GIS technology.

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