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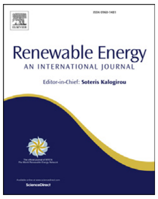

Environmental and economic sustainability of integrated production in bio-refineries: The thistle case in Sardinia

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ABSTRACT

This paper aims at evaluating the environmental and economic sustainability of bio-refineries that produce multiple products through their supply chains (SCs). A physical enterprise input-output (EIO) model is used to quantify the material/energy/waste flows and integrated to the monetary EIO model to compute the economic performance of bio-refinery SC (BRSC). The empirical case study is based on a (under-construction) bio-refinery which uses thistle oil and residues to produce bio-monomers, bio-lubricants, glycerine, and thermal energy in Porto Torres industrial district, Sardinia (Italy). Given the impact of uncertainty on the performance of the BRSC, we apply sensitivity analysis on the spatial, logistical, and biomass quality variables, i.e., land productivity, transportation distance, and thistle oil content rate.

In terms of practical contribution, the physical and monetary EIO models serve as planning and accounting tools for the involved companies of the BRSC. Findings show that the proposed models are effective in evaluating the sustainability of BRSCs and the investigated variables may significantly influence the economic viability of the bio-refinery. From managerial perspective, pricing contracts between the thistle producers and the bio-refinery is critically driven by the transportation distance. The bio-refinery can produce economically competitive outputs with an important contribution to the region's employment market.

1. Introduction

In the recent, the development of bio-based industry has accelerated in Europe thanks to the EU's circular economy policy which gives impetus to the economy-wise adaptation of sustainability through new business models. Hence, EU supports and encourages the (re-)use of bio-resources to create value-added with reduced environmental impacts in the bio-based industry [44]. In this context, bio-refineries play a crucial role in processing bio-resources into materials, bio-products, feed, heat, and transportation fuels in an integrated production system. While the economic viability of second-generation bioenergy is still a challenge, bio-refineries offer to add value to biomass supply chains by producing bio-based chemicals (e.g. bio-monomers, bio-lubricants, glycerine, starches) [10].

The existence of multi-production pathways in bio-refinery supply chains (BRSC) raises some concerns such as the best-performance route selection and design, influenced by spatial (e.g., land dispersion, land productivity), logistical (e.g. energy density, transportation distance), and technological variables (e.g., mass recovery rate). Furthermore, in biomass supply chains, supplier-buyer relations are not easy to be stable because of seasonality, fluctuating harvest rates or biomass quality. Hence, farmers and biomass processing companies are usually hesitant for signing continuous supply contracts. However, as bio-refineries are able to recover secondary waste streams within their own processes, they are able to produce more value-added compared to one technology-based production. This allows bio-refineries to be more flexible with contracts compared to bioenergy companies. In addition, large-mass production in bio-refineries is still not

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available and the research is ongoing to overcome technological barriers. Process technology integration is a promising strategy to increase the economic sustainability of bio-refineries. As most bio-refineries are designed according to the availability of local resources, different combinations of process integrations are observed in different cases (e.g. Ref. [21]. The empirical case of this paper deals with the use of thistle, which is a rich bio-resource that allows the producer to produce bio-products, namely bio-monomers, bio-lubricants, and glycerine (from thistle seed) and bio-energy (from thistle residues) in the Porto Torres industrial district, Sardinia (Italy). The bio-refinery is still under construction and expected to be operative by 2017.

This paper firstly aims at evaluating the environmental and economic sustainability of the thistle-based BRSC via enterprise input-output (EIO) modelling. Second, it assesses the effects of above-mentioned variables on the BRSC's performance. Third, it provides managerial and practical contributions to the practitioners to better design BRSCs.

This paper analyses the economic viability and the environmental impacts of the abovementioned bio-refinery in Porto Torres, assessing its whole supply chain. In particular, we analyse the acceptability of the agreed biomass prices between the bio-refinery and Coldiretti (Italian Agricultural Entrepreneurs Association) via measuring total value-added and profit created by the BRSC. We further quantify the CO_2 emissions along the BRSC. For both computations, we claim that the results will fluctuate according to three main variables, i.e., thistle productivity, transportation distance, and thistle oil content. Hence, we apply sensitivity analysis to these three variables and compare sustainability indicators and assess the competition power of bio-based products against their fossil-based counterparts.

We adopt a physical enterprise input-output (EIO) model to compute the material/energy/waste flows of the BRSC and integrate it to the monetary EIO model via cost/price vectors. Having the advantage of tracing inputs, outputs, and the secondary outputs, EIO approach is a suitable tool for evaluating the environmental and economic performance of BRSCs. The physical EIO model serves as a planning tool while the monetary EIO model serves as an accounting tool for the BRSC actors, i.e. farmers, third party logistics players, and the bio-refinery. The rationale of computing first the physical flows is to be able to calculate the technical coefficients among supply chain processes. This also allows us to compute several environmental performance indicators for different levels of production. Then, coefficient matrices are multiplied by unit cost/price vectors and monetary input-output table is computed. This serves as an accounting tool for measuring economic sustainability. Once the physical and monetary flows are computed, then we apply sensitivity analysis to three variables (i) land productivity, (ii) biomass transportation distance, and (iii) thistle oil content rate. For each scenario, we compute the economic and environmental performance indicators and discuss the results comparatively. CO_2 emissions serve as environmental sustainability indicators while average prices of final outputs, total supply chain profit and value-added serve as economic sustainability indicators. Selection of sustainability indicators is based on the variables' impacts on harvesting, transportation and processing phases which commonly contain energy consumption and CO_2 emissions. Missing data do not allow us to apply neither LCA nor a comparison with a literature study as the use of thistle in bio-refineries has not been analysed at large-scale level. For economic sustainability, we particularly compute the average output prices to understand whether the bio-refinery products are market-competitive against their traditional counterparts. Generated profit is measured as a traditional economic performance indicator while the value-added is computed to evaluate the regional socio-economic contribution of the BRSC.

This paper is structured as follows: Section 2, drawing on literature, provides a review of the role of bio-refineries in implementing new business models, critical performance variables in BRSCs, and the use of input-output modelling for supply chain analysis. Section 3 describes the enterprise input-output (EIO) model. In Section 4, the case study is explained, proposed EIO model is applied to the case study and sensitivity analysis is performed. Results are discussed over sustainability indicators in Section 6. The paper is concluded by managerial and practical implications and contributions in Section 7.

2. Literature review

In developed countries, governments develop different strategies to improve the role of bio-refineries within bio-economy. Staffas et al. [34], review the efforts of most of the OECD countries comparatively. Their findings show that three major cross-cutting strategies exist for all countries investigated in the review: “(i) the balance between sustainability and economic aspirations, (ii) the limited attention to measuring progress, and (iii) the challenge of a limited supply of resources.” Indeed, the sector needs economic improvements as the versatile use of biomass does not allow to receive high amounts of supply from suppliers. Increasing the amount of supply would permit the companies to take advantage of the economies of scale and produce more market-competitive products. Hence, non-food local bio-resources, e.g. thistle, with low market competition are suitable for bio-refineries.

On the other hand, increasing the number of biomass suppliers and using more biomass in bio-refinery supply chains (BRSC) depend on the spatial dispersion of biomass, the quality of logistical infrastructure, and the advancements in processing technologies. Accordingly, the supply quantity is influenced by several variables causing uncertainty within BRSCs. Awudu and Zhang [2] discuss five types of uncertainties in biofuel supply chains which are adoptable also for BRSCs. These uncertainties are categorised as: (i) biomass supply, (ii) transportation and logistics, (iii) production and operation, (iv) demand and price, and (v) other uncertainties. Additionally, such uncertainties trigger each other and render the material planning harder for companies caused by less economic clarity. This motivates us to apply sensitivity analysis to three variables in our case study: (i) land productivity, (ii) biomass transportation distance, and (iii) thistle oil content rate.

The companies, facing such planning problems, consequently have difficulty also in the performance-measuring process. Even though literature covers a wide range of studies adopting different methodologies for supply chain design and organization, in performance measuring, life cycle assessment (LCA) is the most common one [26]. The review of Awudu and Zhang [2] addresses two main methodologies to model uncertainties: (i) analytical and (ii) simulation methods. Additionally, de Meyer et al. [11], reviews the biomass supply chain optimization methods as linear, integer, mixed integer linear, and non-linear programming. Sharma et al. [32], classifies the supply chain models as: stochastic, deterministic, hybrid, and IT-driven models. Being a recent joint-venture of two large-scale Italian companies based on highly innovative research, our case study offers us limited data. Hence, available data does not allow us to apply an LCA study or optimization technique. This article aims at understanding a generic picture of a bio-refinery installation and its basic economic and environmental performance.

Input-output modelling is used as an environmental sustainability assessment tool (e.g. Ref. [36], as a hybrid model combined with LCA (e.g. Ref. [43], and as an ecological footprint measuring tool [40]. Wiedmann et al. [39], review the input-output models for environmental impact assessment. Suh and Nakamura [35] review the hybrid use of input-output modelling with LCA. Although these methods are different from methodological perspectives, they are commonly used for environmental sustainability monitoring.

Enterprise input-output (EIO) modelling, on the other hand, can be used both as a planning and accounting tool and as a performance measuring tool for companies [25], supply chains [41], production lines [20], and industrial districts [1]. We adopt the EIO modelling approach in this paper as it allows us to use production processes as the unit analysis. Accordingly, we are able to reveal the economic relations between the BRSC actors, who are categorised as biomass suppliers, third party logistics players, and bio-refinery. We compare several economic and environmental performance indicators in our case study, but do not aim at applying an LCA as the available data does not permit us to provide an in-depth inventory construction to apply a proper LCA.

Most of the bio-refinery processes are pilot or small-scale [14]. Laser et al. [21] compare 14 configurations. Among these 14 configurations 9 are ethanol production combined with different protein or power production such as Fischer-Tropsch fuels, Rankine power, or H_2, while 5 of them are only power production oriented such gas turbine combined cycle, H2, and Rankine power. Among these, bio-chemical and thermo-chemical processing and bio-chemical processing integrated with protein production or power generation appear as the most economically convenient combinations. In our case study, we analyse the integration of bio-monomer production and bio-lubricant production. In the bio-monomer production, first the vegetable oil is oxidized by oxygenized water and air. Then, the obtained mix is distilled and triglycerides and pelargonic acid are produced. Pelargonic acid is sent to the bio-lubricant production while triglycerides are hydrolysed and bio-monomer is produced through separation and purification. Palmitic-steraic acid is the by-product of hydrolysis phase of bio-monomer production and it is also sent to bio-lubricant production. Acids received from bio-monomer production are used together with alcohols in the esterification and bio-lubricants are produced [17]. Hence, secondary waste stream loops are closed and process integration is achieved.

To deal with managerial challenges and adapt to new business models, companies in bio-refining sector should better understand the cost drivers. Since the bio-refineries use extensively second- and third-generation biomass streams or wastes emerging from industrial supply chains, the feedstock markets evolve different than conventional feedstock markets. Parajuli et al., [26]; in their review on the sustainable bio-refinery value chains, find that 40–60% of the total operating costs of a typical bio-refinery is related to feedstock chosen. However, their analysis, similar to extensive literature, is on cellulose and hemicellulose processing where they analyse bioethanol, protein, and feed production. We apply a similar analysis and measure the value-added contributions and environmental impacts of three actors involved in the thistle BRSC: (i) agriculture, (ii) transportation, and (iii) bio-refinery.

The main characteristic of bio-refineries is that they are capable of converting multi-feedstock via multiple technological options into multi-outputs. Currently chemical industry is producing hydrocarbon intermediates (e.g. benzene, xylene, and toluene) from fossil fuels causing high-energy consumption and environmental damage. Therefore, bio-refineries represent a novel and sustainable way of alternative platform for chemicals production [6]. Coututrier [9] analyses the role of different biomass feedstock, such as castor and safflower crambe for bio-monomer production, in bio-refining sector. To render bio-refineries more attractive for suppliers, he evaluates bargaining power of biomass suppliers and bio-refineries and the threat of new competitors and substitute products. Specific to the castor which is mostly grown in India, he concludes that not only governments but also non-governmental organizations should be aware of the potential and subsidies can enforce the creation of new value chain. Lemonidou [22] raises the issue of aviation fuels production in bio-refineries. She analyses the case of alcohol fermentation to produce C4 alcohols which can substitute fossil-based aviation gasoline and jet fuels. Her findings are promising in terms of market competition and value-chain creation. She ranks the strengths as the products' high volume and value-added, existence of know-how among companies on process steps and sustainable production. As weaknesses, she highlights high technology costs and the certification process for fuels. In this study, CO_2 tax increase for governments and new business chance for aviation fuel producers are emphasized as opportunities while product competition and presence of alternative technologies (such as Fischer-Tropsch) are ranked as threats. Obviously, producing aviation fuel would mean the creation of a new value chain which is a highly diversified supply chain composed of different actors from different sectors. This further triggers new business models among companies that are not traditionally used to cooperate and create new channels for employment. Roelant and Cavani [31] discuss the issue of upstream and downstream process integration in bio-refineries which enable companies to reduce operational and market risks and logistical costs. Such savings for companies can be used in investing bio-refining technologies to reduce market barriers for bio-based products and increase operational efficiency of bio-refineries. This would further trigger regional sustainable development.

Dealing with the primary, secondary and tertiary waste streams leads to some technological drawbacks in bio-refineries. Non-uniform structure and bio-chemical composition of biomass leads to technological inefficiencies. Cherubini and Strømman [8] discuss the key reactions where major improvements are necessary in lignocellulosic bio-refineries and propose chemicals recovery as a value-adding and efficiency-increasing option.

A significant amount of articles in bio-refinery research are related to bio-technology developments and feedstock types. Hatti-Kaul et al. [29] compare the advantages and drawbacks of several bio-technologies to produce bio-materials, e.g. bioplastics from corn, oleo-chemical products for wood coatings. Gabrielle et al. [3] discuss how the large-scale biomass supply can be attracted to bio-refineries thanks to technological and research developments. They further discuss the advantages of introducing annual/plurennial cropping systems instead of perennial cropping systems. Ragauskas [28] states that the future of bio-refineries is strongly dependent on the integration of biomass processes to produce food, feed, energy, chemicals, and materials. Fobert et al. [13] provides a supportive example from Canadian context where non-food crucifers are used to extend the variety of fatty acids with a growing area of approximately 15M acres. Van Beilen [37] emphasizes the importance of transgenic plants as an alternative bio-resource to produce polymers, chemicals, and materials considering the high-energy consumption during their production - 5% of current petroleum consumption - [27]. A demonstration plant is being constructed in Havelland (Germany) which will be capable of processing 20.000 t of alfalfa and grass biomass to produce proteins, feed, and biogas [19]. This will be a critical demonstration of regional bio-resource use and process integration as the region provides 10 t dry matter/ha to the existing crop drying plant to which the bio-refinery will be integrated. The reader is advised to refer to Griffith et al. [16], for a detailed comparison of bio-refinery feedstock, Cherubini and Strømman [8] for a comprehensive review of up-to-date technological developments in bio-refineries. The reader is further suggested to see Mandl [24] and the final report of Euro-Bioref project financed by EC [12] for the efforts in EU countries.

In the up-to-date literature, there are limited studies regarding thistle use in bio-refineries. Wan Isahak et al. [38], addresses the slow pyrolysis of thistle in a fixed-bad reactor. Ramirez and Seco [30] only compare the combustion residue emissions of thistle with other biomass types. However, a comprehensive thistle-based BRSC analysis is not available in the literature. This paper fills this gap by providing the case study of thistle in Sardinia. We compare the final output prices with their fossil-based correspondents so that we can understand whether the principal outputs are market-competitive.

3. Enterprise input-output model for bio-refinery supply chains

The enterprise input-output (EIO) model proposed in this section contains physical a monetary flows among the processes of bio-refinery supply chains. Hence, it is usable for different case studies as well. Three types of flows are modelled: (i) main inputs/outputs produced by supply chain processes, namely intermediate deliveries, (ii) primary inputs purchased out of the supply chain, and (iii) wastes and by-products produced as secondary outputs by the processes of supply chain.

Let Z_0 be the matrix of domestic (i.e. to and from production processes within the BRSC) intermediate deliveries, f_0 is the vector of final demands, and x_0 the vector of gross outputs.

If n processes are considered, the matrix Z_0 is of size n x n, and the vectors f_0 and x_0 are n x 1. Each process has a single product as its main output.

There are s primary inputs, not produced by one of the n production processes but purchased from out of the BRSC. Next to the main outputs, the processes also produce m by-products and wastes. r_0 and w_0 are the primary input vector, and the by-product/waste vector of size s x 1 and m x 1, respectively.

Then, we shortly describe the equations adopted from Yazan et al. [41]. Define the intermediate coefficient matrix A as follows:

$$A = Z_0 \hat{x}_0^{-1} \tag{1}$$

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

$$x_0 = Ax_0 + f_0 = (I - A)^{-1} f_0 \tag{2}$$

It is possible to estimate R, the s x n matrix of primary input coefficients with the 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_{lj} denoting the output of by-product or waste type l (1, …, m) per unit of output of process j. It results:

$$r_0 = Rx_0 \tag{3}$$

$$w_0 = Wx_0 \tag{4}$$

The EIO model can be also adopted to account the monetary value associated with each production process. In particular, let p_0 be the vector of the prices with element p_i denoting the unitary price of the main product of the process i (i.e. no downstream transportation is included meaning that the process utilizing transportation as input pays for it). Thus, considering the vector of the gross outputs x_0, we can compute the vector y_0, representing the total revenues associated with each gross output as follows:

$$y_0 = \hat{x}_0 p_0 \tag{5}$$

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

$$b_{ij} = a_{ij} \frac{p_i}{p_j} \tag{6}$$

Then, we have:

$$y_0 = By_0 + \hat{f}_0 p_0 = (I - B)^{-1} \hat{f}_0 p_0 \tag{7}$$

The matrix B is of size n x n, and the vectors $\hat{f}_0 p_0$ and y_0 are n x 1. Moreover, we can define the vector of the prices (or costs) p_0^w which is a m x 1 vector, where its element p_i^w represents the unitary price (or cost) associated to the by-products (or wastes) in all processes (i.e. by-product represents economic gains and waste represents treatment costs). Hence, using the matrix W, we can identify the vector y_0^w , a n x 1 vector, representing the total revenues associated with all by-products for each process as follows:

$$y_0^w = \left[\left(p_0^w \right)^T W \hat{x}_0 \right]^T \tag{8}$$

In addition, let y_0^r (n x 1 vector), be the vector of the costs associated to each process for the primary inputs, including wages and salaries (i.e. workforce is considered as primary input), and d_0 which is a n x 1 vector for investments amortization (observed data). For the accounting of all types of primary inputs, the unitary price vector p_0^r (s x 1), is defined in order to calculate y_0^r. The vector of intermediate inputs costs y_0^z , (n x 1), is also calculated using $\hat{p}_0$ and i (n x 1 unit vector, having all elements equal to one).

$$y_0^r = \left[\left(p_0^r \right)^T R \hat{x}_0 \right]^T \tag{9}$$

$$y_0^z = \left[(i)^T \hat{p}_0 A \hat{x}_0 \right]^T \tag{10}$$

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

$$\prod = \sum_{i=1}^{n} \left(y_i + y_i^w - y_i^z - y_i^r - d_i \right) \tag{11}$$

4. Case study

This section provides a description of the case study, followed by the explanation for model assumptions.

4.1. Case study description

The industrial district of Porto Torres (Sardinia, Italy) is constructed near the port of Porto Torres with an old petrochemical production unit. With the initiatives of several stakeholders from the industrial district and the regional authorities, two multinationals have decided to invest in a 450M joint venture to construct a bio-refinery in the district. The bio-refinery aims at using the thermal energy produced by second-generation biomass (e.g. thistle residues) and process vegetable oil (e.g. thistle seed oil) to obtain biodegradable monomers, glycerine, and bio-lubricants in the first phase. After the completion of the second and third phase, the Polo Verde (the Green Pole) is aimed to be the biggest centre for green chemistry in Europe. This objective will be achieved throughout the creation of a bio-refinery with an integrated production chain: from raw materials and local agricultural residues to the final products. The second phase include the production of bio-additives for pneumatics and bio-fillers, while the third phase intends to produce bioplastics.

Even though the bio-refinery will be capable of processing a wide range of vegetable oils, we consider the use of thistle oil in the bio-refinery as it is one of the mostly cultivated non-food plant in Sardinia. Thistle has a productivity of 1.2–1.8 t of thistle seed/ha and 12–18 t of thistle residues/ha in absence of irrigation. In particular, thistle is extremely appealing since it also contains substances with high value added like protein meals and nectar.

The experimentation in Sardinia, which began in autumn 2011 with the planting of about 15 ha of thistle on marginal lands, continued in 2012 with the planting of additional 180 ha of ex-wheat cultivated land. On the other hand, the productivity of thistle in the first year of cultivation in Sardinia was about 11 t/ha of thistle residues and 0.76 t/ha of thistle seed, increased by the second year to 17 t/ha of thistle residues and 1.9 t/ha of thistle seed.

The bio-refinery processes will employ thistle seed while a cogeneration unit will use the thistle residues to produce heat. The total heat requirement of the bio-refinery will be obtained from this cogeneration unit. The collection of thistle straw occurs in a radius of 70 km from Porto Torres industrial area, which is accepted as economically sustainable distance from logistical perspective. The supply basin for the thistle biomass is depicted in Fig. 1 [4]. The thistle fields which are expected to supply the bio-refinery are located in Sassari province which has 246,822 ha of arable land [4]. Being Porto Torres a port town with a large industrial district, the quality of transportation infrastructure within the province can support the transportation of biomass.

The bio-refinery is planned as a network of 41 units, which are aggregated under seven main processes in our paper, i.e. (i) thermal energy production, (ii) oxidation & distillation, (iii) hydrolysis, (iv) separation & purification (for the bio-monomer plant), and (v) blend preparation, (vi) esterification, and (vii) finishing (for the bio-lubricant plant). These processes are preceded by thistle seed cultivation, thistle residues harvesting, transportation, and thistle oil production. Thus, in total the bio-refinery supply chain (BRSC) contains 11 processes, each producing one main output. There are also primary inputs (e.g. gasoil, workforce, electricity), wastes (CO_2, effluent water), and by-products recycled (e.g. palmitic stearic acid, pelargonic acid) within the bio-refinery or sold as a value-added (e.g. glycerine). Fig. 2 displays the primary material/energy/waste flows of the BRSC.

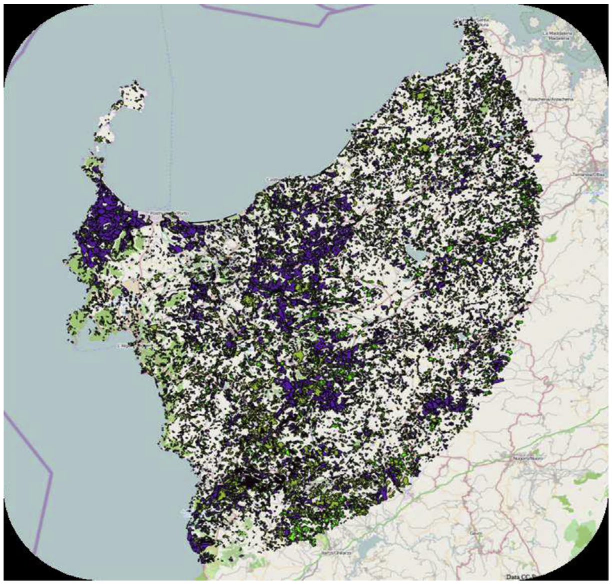

Fig. 1. Supply area of thistle [4].

4.2. Assumptions

First, we construct the base scenario where we assume the collection of thistle seeds (1.5 t/ha) and residues (15 t/ha) in 67,000 ha of thistle land with a transportation distance of 70 km. We also assume that 75% of the thistle residues are collected and the rest is left on the field to protect soil fertility. Available literature shows different oil content rate for thistle which varies between 20 and 35% [23]. We assume 30% oil content rate in our basis scenario. These are the main assumptions regarding the preceding processes of the bio-refinery and we apply sensitivity analysis to these variables in further scenarios.

Data regarding biomass transportation and thistle residues collection are adopted from Yazan et al. [41] and Yazan et al. [42]. Data regarding bio-refinery processes are elaborated from ICARO [17,18].

In the bio-refinery, we assume that the produced thermal energy is equally divided among oxidation & distillation (P6), hydrolysis (P7), separation & purification (P8), and esterification (P10). Similarly, we know that the bio-refinery will use 24,800 MWh/year [17] distributed among all processes between P6 and P10. Such assumptions are due to the fact we have total energy use data for the bio-refinery, which is not disaggregated at process level.

Costs for BRSC can be categorised as input purchasing costs, transportation costs, workforce cost, and investment costs.

In the supply planning phase, according to the agreement between the bio-refinery and Coldiretti (Italian Agricultural Entrepreneurs Association), the bio-refinery will pay 200 €/t of thistle seed and 45 €/t of thistle residue. Transportation cost is to be paid by the thistle farmers and it is 60 €/hour. Average workforce cost is 15 €/hour [42], fertilizer purchasing cost is 230 €/t [41], gasoil purchasing cost 1.2 €/l and electricity purchasing cost is 142 €/t. H_2O_2 [33] and alcohols (octanol [5], purchasing costs are 446 and 1172 €/t, respectively. We also take into account the CO_2 tax which is 14.88 €/t [7].

The investment is 100M € for the bio-refinery [18]. 15 years of operation is assumed and accordingly investment costs are distributed among bio-refinery processes.

For each final product, i.e., bio-monomer and bio-lubricant, bio-refinery adds a mark-up of 10% to the total costs. For the by-product glycerine, on the other hand, we assume that it is sold at the market price level of traditional glycerine (i.e., 837 €/t [15], for market competition reasons. Obviously, above-mentioned assumptions have impact on the economic returns. Fluctuations on biomass yield caused by several reasons such as seasonality might lead to operational inefficiencies reducing economic benefits. Hence, we use the average values of thistle seed and thistle residues harvest, i.e., 1.5 t/ha and 15 t/ha and a transportation distance of 70 km. These values are the expected mean values by the bio-refinery and the bio-refinery made the price agreements with Coldiretti according to these mean values. We aim at understanding whether such agreements can result in economically sustainable products. Hence, we apply sensitivity analysis to the physical variables keeping agreed prices constant and observe how the profitability of the BRSC changes accordingly. To this aim, we compare our findings with the traditional counterparts' market prices. Table 1 displays the technical coefficients table of the BRSC.

5. Results

Tables 2 and 3 represent the physical and monetary input-output table.

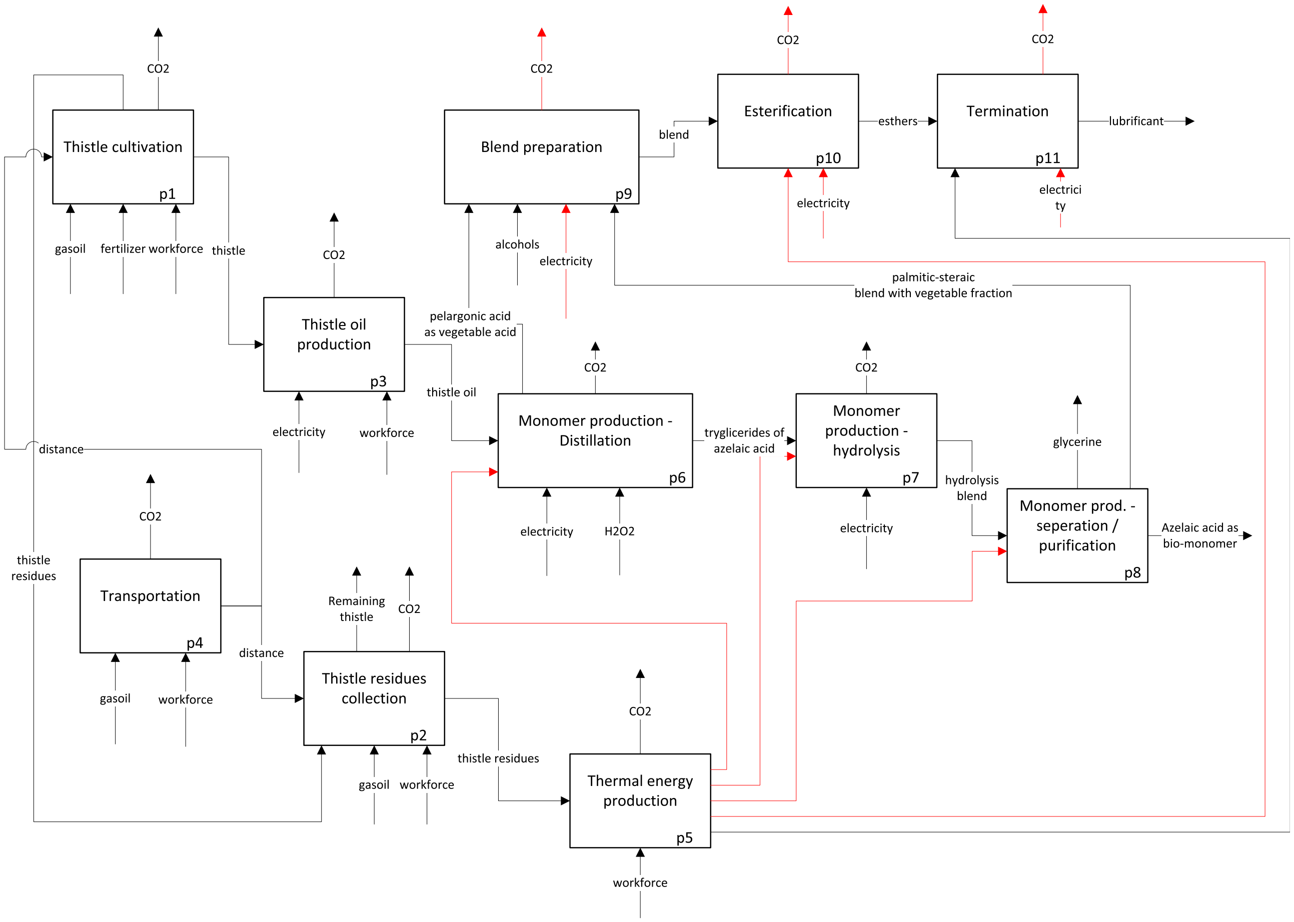

Fig. 2. BRSC flowchart.

Some of the by-products (e.g. pelargonic acid, palmitic stearic acid) are reused within the BRSC. For such by-products we do not attribute a cost or price. On the other hand, glycerine is sold in the market and effluent water is treated within the bio-refinery.

We see from Table 1, the bio-refinery produces 17,000 t of azelaic acid as bio-monomer, 17,000 t pelargonic acid and 2500 t palmitic stearic acid as vegetable acid (to be employed in bio-lubricant production), 2700 t of glycerine, and 30,000 of bio-lubricants per year. Thus, pelargonic acid and palmitic steraic acid are the outputs of bio-monomer production, which, then become inputs for bio-lubricant production. The products marketed are glycerine, azelaic acid (as bio-monomer), and bio-lubricant. We evaluate three sustainability indicators measured on unit output and unit profit, namely CO_2 emissions, employment created, and energy use. In addition, we compare the price of the output mix (azelaic acid, glycerine, and bio-lubricant) with their conventional correspondents. Results of the base scenario, where the land productivity is 1.5 t thistle seed/ha, oil content rate is 30%, and the transportation distance is 70 km, are summarized in Table 4.

Sensitivity analysis is applied on three parameters, i.e., land productivity, transportation distance, and thistle seed's oil content. Results are summarized on Figs. 3–9.

6. Discussion

6.1. Economic sustainability analysis

As the bio-refinery produces three main outputs, we first find the average price for the output mix composed of 34% azelaic acid, 60% bio-lubricant, 6% glycerine. To do so, we simply divide the revenue obtained from the sales of these products to their total weight. We obtain an average price of 1321 €/ton which is in the range of the correspondent conventional products' price. We define a minimum and maximum price for the conventional product mix of glycerine, azelaic acid, and bio-lubricant, which is between 1148 and 2542 €/t. Pricing is a matter of cost accounting for the bio-refinery. In case of direct-costing, since there is a considerable amount of mass loss in bio-monomer production (as pelargonic and palmitic stearic acids are sent to lubricant production), the unit price of the azelaic acid appears to be 2259 €/t which is not competitive in conventional markets. In contrast, using direct costing, bio-lubricant price is less than its conventional substitutes. However, with a complete cost pooling of production costs, all three types of outputs can compete with their traditional correspondents in the market. Computing the average price of final outputs mix is a reasonable accounting approach as bio-refineries are designed to operate by using secondary waste or by-product streams within their own processes. Particularly in our case, in the bio-monomer production, the bio-refinery produces not only 17,035 t of bio-monomer but also 17,336 t of pelargonic acid which later becomes the most important input of bio-lubricant production. So, the bio-refinery is able to produce 30,311 t of bio-lubricant by using the pelargonic acid deriving from bio-monomer production. If the thistle quantity is reduced by 10%, all of the main outputs will reduce by 10% (unless additional biomass is used), but the percentages of main outputs in the final mix do not vary.

Table 1
Technical coefficients of the BRSC.

Processes			P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
P1	Thistle cultivation	t of thistle seeds	0,00	0,00	3,33	0,00	0,00	0,00	0,00	0,00	0,00	0,00
P2	Thistle residues collection	t of thistle SGB	0,00	0,00	0,00	0,00	0,17	0,00	0,00	0,00	0,00	0,00
P3	Thistle oil production	t of thistle seed oil	0,00	0,00	0,00	0,00	0,00	1,66	0,00	0,00	0,00	0,00
P4	Transportation	km	8,48	8,48	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
P5	Thermal energy production	GJ	0,00	0,00	0,00	0,00	0,00	1,51	1,39	1,61	0,00	0,86
P6	Oxidation/distillation	t of tyriglycerides	0,00	0,00	0,00	0,00	0,00	0,00	0,92	0,00	0,00	0,00
P7	Hydrolysis	t of hydrolysis blend	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,16	0,00	0,00
P8	Separation/purification	t of bio-monomer	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
P9	Blend preparation	t of blend	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,07
P10	Esterification	t of esthers	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
P11	Finishing	t of bio-lubricant	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Primary inputs												
r1	gasoil	liter	1,24	1,75	0,00	0,18	0,00	0,00	0,00	0,00	0,00	0,00
r2	fertilizer	t	0,15	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
r3	workforce	person hour	5,33	0,95	3,19	0,02	1,00	1,20	1,10	1,28	0,64	0,68
r4	thistle residues	t	0,00	1,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
r5	electricity	MWh	0,00	0,00	0,21	0,00	0,00	0,27	0,25	0,29	0,07	0,08
r6	H2O2	t	0,00	0,00	0,00	0,00	0,00	0,38	0,00	0,00	0,00	0,00
r7	palmitic-stearic acid	t	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,07	0,00
r8	alcohols	l	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,42	0,00
r9	pelargonic acid	t	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,51	0,00
r10	water	t	0,00	0,00	0,00	0,00	0,00	0,00	0,08	0,00	0,00	0,00
By-products and wastes												
w1	thistle residues	t	10,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
w2	CO2	t	0,00	0,01	0,09	0,00	0,00	0,12	0,11	0,13	0,03	0,03
w3	remaining thistle	t	0,00	0,33	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
w4	glycerine	t	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,16	0,00	0,00
w5	pelargonic acid	t	0,00	0,00	0,00	0,00	0,00	0,96	0,00	0,00	0,00	0,00
w6	palmitic-stearic acid	t	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,14	0,00	0,00
w7	effluent water	t	0,00	0,00	0,00	0,00	0,00	0,00	0,04	0,00	0,00	0,07

Table 2
PIOT of the case study.

Processes		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	Final demand	Total production
P1	t	0	0	100,500	0	0	0	0	0	0	0	0	0	100,500
P2	t	0	0	0	0	18,698	0	0	0	0	0	0	735,052	753,750
P3	t	0	0	0	0	0	30,150	0	0	0	0	0	0	30,150
P4	km	852,727	6,395,455	0	0	0	0	0	0	0	0	0	0	7,248,182
P5	GJ	0	0	0	0	0	27,486	27,486	27,486	0	27,486	0	0	109,943
P6	t	0	0	0	0	0	0	18,150	0	0	0	0	0	18,150
P7	t	0	0	0	0	0	0	0	19,809	0	0	0	0	19,809
P8	t	0	0	0	0	0	0	0	0	0	0	0	17,035	17,035
P9	t	0	0	0	0	0	0	0	0	0	34,031	0	0	34,031
P10	t	0	0	0	0	0	0	0	0	0	0	31,906	0	31,906
P11	t	0	0	0	0	0	0	0	0	0	0	0	30,311	30,311
Primary inputs													total primary input use	
gasoil	l	124,620	1,319,051	0	1,282,371	0	0	0	0	0	0	0	2,726,041	
fertilizer	t	15,256	0	0	0	0	0	0	0	0	0	0	15,256	
workforce	p.hrs	536,000	714,667	96,207	120,803	109,653	21,724	21,724	21,724	21,724	21,724	21,724	1,707,677	
thistle residues	t	0	753,750	0	0	0	0	0	0	0	0	0	753,750	
electricity	MWh	0	0	6387	0	0	4960	4960	4960	2480	2480	4960	31,187	
H2O2	t	0	0	0	0	0	6935	0	0	0	0	0	6935	
palmitic-stearic acid	t	0	0	0	0	0	0	0	0	2427	0	0	2427	
alcohols	l	0	0	0	0	0	0	0	0	14,268	0	0	14,268	
pelargonic acid	t	0	0	0	0	0	0	0	0	17,336	0	0	17,336	
water	t	0	0	0	0	0	0	1658	0	0	0	0	1658	
Wastes and by-products													total by-products and wastes	
thistle residues	t	1,005,000	0	0	0	0	0	0	0	0	0	0	1,005,000	
CO_2	t	436	4617	2746	4488	0	2133	2133	2133	1066	1066	2133	22,952	
remaining thistle	t	0	251,250	0	0	0	0	0	0	0	0	0	251,250	
glycerine	t	0	0	0	0	0	0	0	2774	0	0	0	2774	
pelargonic acid	t	0	0	0	0	0	17,336	0	0	0	0	0	17,336	
palmitic-stearic acid	t	0	0	0	0	0	0	0	2427	0	0	0	2427	
effluent water	t	0	0	0	0	0	0	829	0	0	2126	0	2955	

Table 3
MIOT of the case study.

Processes	Process 1	Process 2	Process 3	Process 4	Process 5	Process 6	Process 7	Process 8	Process 9	Process 10	Process 11	Final demand	Total production
Thistle cultivation	0	0	20,100,000	0	0	0	0	0	0	0	0	0	20,100,000
Thistle residues collection	0	0	0	0	841,403	0	0	0	0	0	0	33,077,347	33,918,750
Thistle oil production	0	0	0	0	0	22,584,752	0	0	0	0	0	0	22,584,752
Transportation	1,705,455	12,790,909	0	0	0	0	0	0	0	0	0	0	14,496,364
Thermal energy production	0	0	0	0	0	1,084,083	1,084,083	1,084,083	0	1,084,083	0	0	4,336,332
Monomer production-oxidation/distillation	0	0	0	0	0	0	28,778,699	0	0	0	0	0	28,778,699
Monomer production-hydrolysis	0	0	0	0	0	0	0	31,881,231	0	0	0	0	31,881,231
Monomer production-separation/purification	0	0	0	0	0	0	0	0	0	0	0	38,477,579	38,477,579
Lubricant production - blend preparation	0	0	0	0	0	0	0	0	0	18,365,011	0	0	18,365,011
Lubricant production - esterification	0	0	0	0	0	0	0	0	0	0	21,097,495	0	21,097,495
Lubricant production -finishing	0	0	0	0	0	0	0	0	0	0	0	25,422,978	25,422,978
Primary inputs												total primary input use	
gasoil	149,544	1,582,861	0	1,538,845	0	0	0	0	0	0	0	3,271,249	
fertilizer	3,508,857	0	0	0	0	0	0	0	0	0	0	3,508,857	
workforce	8,040,000	10,720,000	1,443,108	1,812,045	1,644,801	325,866	325,866	325,866	325,866	325,866	325,866	25,615,154	
thistle residues	0	0	0	0	0	0	0	0	0	0	0	0	
electricity	0	0	906,976	0	0	704,320	704,320	704,320	352,160	352,160	704,320	4,428,576	
H2O2	0	0	0	0	0	3,095,561	0	0	0	0	0	3,095,561	
alcohols	0	0	0	0	0	0	0	0	16,718,735	0	0	16,718,735	
water	0	0	0	0	0	0	3317	0	0	0	0	3317	
By-products and wastes												total by-products and wastes	
thistle residues	0	0	0	0	0	0	0	0	0	0	0	0	
CO2	6490	68,696	40,868	66,786	0	31,736	31,736	31,736	15,868	15,868	31,736	341,520	
glycerine	0	0	0	0	0	0	0	2,321,671	0	0	0	2,321,671	
effluent water	0	0	0	0	0	0	829	0	0	2126	0	2955	
Amortization cost	496,296	661,728	93,800	1,677,820	1,850,128	952,381	952,381	952,381	952,381	952,381	952,381		10,494,058
Total Costs	13,906,642	25,824,194	22,584,752	5,095,496	4,336,332	28,778,699	31,881,231	34,979,617	18,365,011	21,097,495	23,111,798		229,961,266
Profit	6,193,358	8,094,556	0	9,400,868	0	0	0	5,819,632	0	0	2,311,180		31,819,593
Value-added	14,233,358	18,814,556	1,443,108	11,212,913	1,644,801	325,866	325,866	6,145,499	325,866	325,866	2,637,046		57,434,747

Table 4
Performance indicators of the BRSC.

Performance indicator/data	Parameter	Unit (output mix is 34% azelaic acid, 60% bio-lubricant, 6% glycerine)
conventional glycerine price range	324–647	€/ton
conventional lubricant price range	1113–2781	€/ton
conventional azelaic acid price range	1348–2427	€/ton
conventional output mix price range:	1148–2542	€/ton
unit output mix price from bio-refinery	1321	€/ton
price azelaic acid (bio-monomer) from bio-refinery	2259	€/ton
price bio-lubricant from bio-refinery	839	€/ton
CO_2/output	0.46	t/t
CO_2/profit	1	kg/€
energy consumption/output	6184	GJ/t
energy consumption/profit	10	MJ/€
employment/output	34,072	person.hours/t
employment/profit	0.05	person.hours/€
value-added	56.4M	€

The chain produces a total annual value-added of 57.4M €. Transportation and agriculture produces relatively higher value-added compared to the bio-refinery (Fig. 3). This is due to the labour-based character of these two sectors creating green jobs with a total of 20.5M €/year. We apply 10% mark-up for the final products of the bio-refinery while the transportation, thistles seed, and thistle residues prices are fixed on 60 €/hour, 200 €/ton, and 45 €/ton, respectively. Mark-up can be increased depending on the quality of the final output mix as the price with 10% mark-up is within the price range of its conventional correspondent.

Market sales of thistle residues out of the chain provide a critical revenue contribution of 33M € to the agriculture sector. This causes

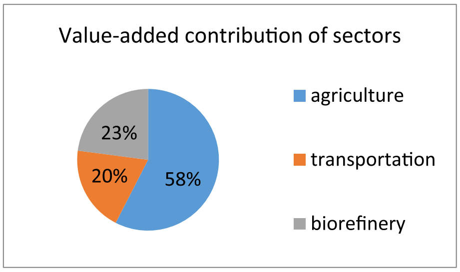

Fig. 3. Value-added contributions of each sector.

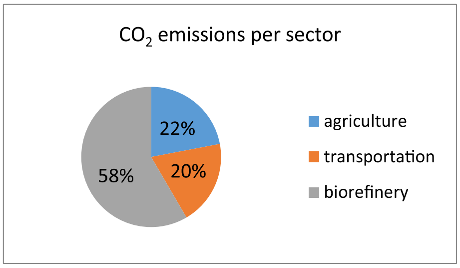

Fig. 4. CO2 emissions from each sector.

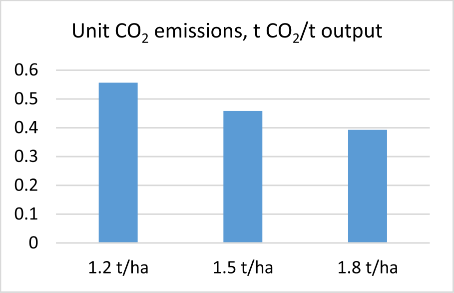

Fig. 5. Unit CO_2 emissions – land productivity.

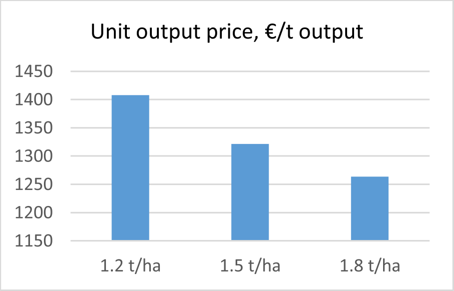

Fig. 6. Unit output price – land productivity.

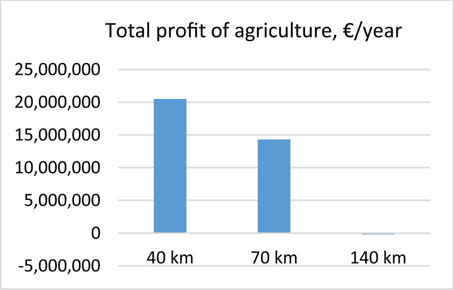

Fig. 7. Agriculture profit – transportation distance.

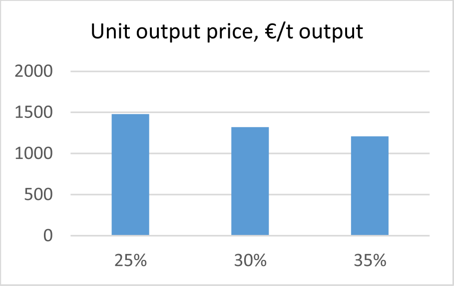

Fig. 8. Unit output price – thistle oil content.

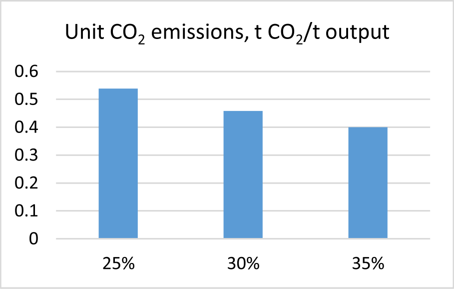

Fig. 9. Unit CO_2 emissions – thistle oil content.

a notable value-added increase in agriculture sector, producing more than 50% of the chain's total value-added.

6.2. *Environmental sustainability analysis*

Most of the CO_2 emissions, ranging between 0.4 and 0.6 t CO_2/t output, are caused by energy use in bio-refinery processes. Fig. 4 displays the CO_2 emission percentages from each sector. Bio-refinery, due to its intensive electricity and heat consumption, contributes more to the CO_2 emissions. Even though the heat is produced from thistle residues, the electricity to be used in the bio-refinery is planned to be fossil-based and this increases CO_2 emissions. Half of the CO_2 emissions occur out of the bio-refinery. In particular, due to high gasoil consumption, each of thistle residues collection and transportation processes causes 20% of total CO_2 emissions, with a sum up to 40%. Bio-refinery foresees a total of 24,800 MWh/year of fossil-based electricity consumption [18] which significantly increases the CO_2 emissions of the BRSC. Obviously, sustainable solutions can be developed to reduce the total CO_2 emissions. A heat and electricity cogeneration plant based on biomass use can feed the bio-refinery or transportation distances can be reduced. Both options would help reducing CO_2 emissions but would also cause additional costs. Differently, biomass can be imported from out of the region reducing the CO_2 emissions within the region. However, this would increase the CO_2 emissions related to long transportation of imported biomass and reduce the positive economic impact in terms of value-added in the region. It is critical to mention that we do not consider land-use change impact on CO_2 emissions as we assume that thistle cultivation areas are actively cultivated. However, depending on bio-refinery's performance, the thistle lands are planned to be gradually enlarged within the region. We aim at applying life-cycle assessment once the bio-refinery launches the operation to get more accurate results.

6.3. *Sensitivity analysis*

Unit CO_2 emissions are negatively correlated with the land productivity and thistle oil content. Similarly, unit energy consumption increases while the productivity decreases. Transportation process has a notable impact on the profit of the agriculture process, as farmers are paid a fixed price for thistle seed and thistle residues by the bio-refinery, i.e. 200 €/t of thistle seed and 45€/t thistle residues, and pay for the transportation. Fig. 8 reveals that to have minimum profit, the transportation distance should be less than 140 km, which leads to a total loss of 220 k €/year for the chain. Sensitivity analysis on transportation distances shows that if the bio-refinery faces operational/logistical problems due to the factors such as land accessibility or transportation infrastructure quality, the collection radius can be reduced (to e.g., 40 km) only if the biomass supply is ensured in a smaller area. In contrast, if the bio-refinery suffers from lack of biomass quantity within 70 km, then collecting thistle from further provinces is not sustainable and alternative feedstock should be supplied. Hence, transportation distance is a very critical factor on the economic sustainability of the BRSC.

Higher the oil content and land productivity less the unit output price, which is in range of the conventional correspondent products' prices. Hence, in all scenarios, independently from the variables investigated, the output price is competitive in the market.

The reuse of by-products from monomer production notably assists the bio-refinery to reduce the feedstock purchasing costs for bio-lubricant production. Similarly, glycerine contributes with 2.3M € to the bio-refinery. Thus, process integration has considerable environmental and economic contributions in terms of resource and energy consumption and cost savings.

6.4. *Shortcomings and strengths*

Our analyses neglect the use and treatment of catalysers as the information about catalysers are kept as commercial secret by the bio-refinery. This is a shortcoming of the paper as catalyser costs can play a serious role in product pricing.

Another shortcoming of the paper caused by missing sensitive data from the company is the transaction costs. Intuitively we can foresee that transaction costs might critically effect the chain's performance as this is a new business model for involved actors and managerial, organizational, and transactional costs will appear once the chain will become operative. Particularly, the organization of logistics in BRSCs is not easy due to the bulky volume of biomass and its dispersion.

The paper provides theoretical contribution in the literature by proposing EIO model as planning, accounting, and performance measuring tool. Adopting the model, each supply chain member can organize its resource planning and the associated costs and revenues.

The representation of the case study provides practical and managerial contributions as it demonstrates that the pricing contracts should take into account the variables investigated in the paper. Indeed, to our knowledge, the bio-refinery signed a contract with Coldiretti (the Italian Agriculture Association) in Sardinia promising 200 €/t of thistle seed and 45 €/t of thistle residues. In case, the costs of production exceeds the promised price, then bio-refinery holds the responsibility of paying the cost difference. However, this might not be possible for all thistle lands, particularly for the most distant and difficultly accessible ones. In such cases companies tend to re-arrange the feedstock supply due to supply price problems triggered by operational inefficiencies, spatial conditions, or seasonality impacts. In fact, the processing technology of the bio-refinery allows to use high-oleic sunflower oil, brassica carinata oil, or crambe abyssinica as a back-up option, which means that local thistle supply chain might not completely be integrated to bio-refinery production.

The role of local government is also significant in the BRSC, as the marginal thistle lands are also extensive in the region. These lands are expected to contribute the supply and require careful farming to reduce feedstock quality uncertainty. High-level strategical cooperation between the bio-refinery, Coldiretti, and the local government is, therefore, inevitable.

7. Conclusions

In this paper, we adopt an EIO model to analyse the environmental and economic sustainability of a BRSC in the specific case of Sardinia. The model allows us to integrate the physical flows with the monetary flows and evaluate the environmental and economic performance indicators.

The region has faced environmental concerns due to the intensive petro-chemical activities in Porto Torres industrial area in the past decades. Hence, the construction of the bio-refinery would help the region to rely on its local renewable resources, producing sustainable products and energy with reduced environmental impact. This, further triggers the creation of green jobs via the integration of agricultural and industrial supply chains. In our scenario analysis we assume that there is enough demand within the region for the principal products. However, in case of demand lack, the products can be exported out of the region, inducing additional impact on the regional economy.

The BRSC triggers a total revenue of 260M €. The bio-refinery allows the practitioners to connect traditionally separate sectors as the use area of main products are diverse, e.g. pharmaceutical, cosmetics, packaging. Furthermore, the cultivation of thistle is strongly encouraged by regional authorities leading to re-vitalize the agriculture of the region. This is in line with the EU's regional development strategies and activates the circular economy in Sardinia.

The performance of the BRSC is strongly influenced by several variables, investigated in a sensitivity analysis. Even though the uncertainty about land productivity, transportation distance, and oil content is high, the BRSC performs well and produces price-competitive bio-monomer, bio-lubricant, and glycerine.

Further research aims at measuring the overall regional contribution of the Porto Torres bio-refinery to the Sardinia region. We intend to integrate the MIOT constructed in this paper into the regional input-output tables of Sardinia, so that we can also compute the indirect and induced impacts of the BRSC. Then, we can further compute not only the export potential of the region but also the opportunities and strategies to attract new actors to the region. These actors might be both upstream and downstream actors of the BRSC, such as recyclers of catalysers, effluent water treatment companies, and chemicals purification companies.

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References

[1] V. Albino, E. Dietzenbacher, S. Kuhtz, Analysing materials and energy flows in an industrial district using an enterprise input–output model, Econ. Syst. Res. 15 (2003) 457–480.

[2] I. Awudu, J. Zhang, Uncertainties and sustainability concepts in biofuel supply chain management: a review, Renew. Sustain. Energy Rev. 16 (2012) 1359–1368.

[3] B. Gabrielle, L. Bamière, N. Caldes, S. De Cara, G. Decocq, F. Ferchaud, C. Loyce, E. Pelzer, Y. Perez, J. Wohlfahrt, G. Richard, Paving the way for sustainable bioenergy in Europe: technological options and research avenues for large-scale biomass feedstock supply, Renew. Sustain. Energy Rev. 33 (2014) 11–25.

[4] Bastioli C. 2016 A concrete example of fully integrated biorefinery in Italy. Workshop on building new biomass supply chains for the bio-based economy. Alghero, Italy, May 27–28. Available at: https://ec.europa.eu/eip/agriculture/sites/agri-eip/files/field_event_attachments/ws-bioeconomy-20150527_catia_bastioli.pdf.

[5] Bessie Chen Anhui Eapearl Chemical Co., Ltd, Price for Alcohols – Octanol, 2016. Available at: https://www.alibaba.com/product-detail/2-Octanol-mono-ethylene-glycol-price_60410643185.html.

[6] S. Blanco-Rosete, G. Webb, Emerging biorefinery markets: global context and prospects for Latin America, Biofuels, Bioprod. Bioref. 2 (2008) 331–342.

[7] Centre for Climate and Energy Solutions, Options and Considerations for a Federal Carbon Tax, 2013. Available at: http://www.c2es.org/publications/options-considerations-federal-carbon-tax.

[8] F. Cherubini, A.H. Strømman, Chemicals from lignocellulosic biomass: opportunities, perspectives, and potential of biorefinery systems, Biofuels, Bioprod. Bioref. 5 (2011) 548–561.

[9] J.L. Couturier, Connecting feedstock availability and market opportunities: case study on a Madagascar and a European vegetable oil biorefinery, in: Joint Biorefinery Conference, Brussels, Belgium, February 11–12, 2014.

[10] E. de Jong, A. Higson, P. Walsh, M. Wellisch, Product developments in the bio-based chemicals arena, Biofuels, Bioprod. Bioref. 6 (2012) 606–624.

[11] A. de Meyer, D. Cattrysse, J. Rasinmäki, J. Van Orshoven, Methods to optimise the design and management of biomass-for-bioenergy supply chains: a review, Renew. Sustain. Energy Rev. 31 (2014) 657–670.

[12] European Commission EuroBioref project final report. Accessible at: http://cordis.europa.eu/docs/results/241/241718/final1-d11-1-6-finalpublicreport-cnrs-240714-vf.pdf.

[13] P.R. Fobert, M.A. Smith, J. Zou, E. Mietkiewska, W.A. Keller, Developing Canadian seed oils as industrial feedstocks, Biofuels, Bioprod. Bioref. 2 (2008) 206–214.

[14] S.J. Gerssen-Gondelach, D. Saygin, B. Wicke, M.K. Patel, A.P.C. Faaij, Competing uses of biomass: assessment and comparison of the performance of bio-based heat, power, fuels and materials, Renew. Sustain. Energy Rev. 40 (2014) 964–998.

[15] Ginny Wang Fushun Dongke Wax Industry Co., Ltd, Price for Glycerine, 2016. Available at: https://www.alibaba.com/product-detail/vegetable-high-purity-glycerin-producers_2008143475.html.

[16] A.P. Griffith, Francis M. Epplin, Samuel D. Fuhlendorf, Robert Gillen, A comparison of perennial polycultures and monocultures for producing biomass for biorefinery feedstock, Agron. J. 103 (3) (2011) 617–627.

[17] ICARO, Polo verde - Fase I. Impianti per la produzione di monomeri ed oli lubrificanti, biodegradabili, da oli vegetali naturali: Sintesi non tecnica, 2011. Available at: http://www.eib.org/infocentre/register/all/53222448.pdf.

[18] ICARO, Polo verde - Fase I. Impianti per la produzione di monomeri ed oli lubrificanti, biodegradabili, da oli vegetali naturali: SEZIONE III – Quadro di riferimento Progettuale, 2011. Versione predisposta ai fini dell'accessibilità del pubblico. Available at: http://www.sardegnaambiente.it/documenti/18_357_20110909115150.pdf.

[19] B. Kamm, C. Hille, P. Schönicke, G. Dautzenberg, Green biorefinery demonstration plant in Havelland (Germany), Biofuels, Bioprod. Bioref. 4 (2010) 253–262.

[20] S. Kühtz, C. Zhou, V. Albino, D.M. Yazan, Energy use in two Italian and Chinese tile manufacturers: a comparison using an enterprise input-output model, Energy 35 (2010) 364–374.

[21] M. Laser, E. Larson, B. Dale, M. Wang, N. Greene, L.R. Lynd, Comparative analysis of efficiency, environmental impact, and process economics for mature biomass refining scenarios, Biofuels, Bioprod. Bioref. 3 (2) (2009) 247–270.

[22] A. Lemonidou, Biobased aviation fuels: creation of a new value chain from lignocellulosic materials, in: Joint Biorefinery Conference, Brussels, Belgium, February 11–12, 2014.

[23] M. Malekzadeh, S.I. Mirmazloum, H. Rabbi Anguorani, S.N. Mortazavi, M. Panahi, The physiochemical properties and oil constituents of milk thistle (Silybum marianum Gaertn. Cv. Budakalaszi) under drought stress, J. Med. Plants 5 (8) (2011) 1485–1488.

[24] M. Mandl, Status of green biorefineries in Europe, Biofuel Bioprod. Bioref. 4 (2010) 316–322.

[25] G. Marangoni, G. Fezzi, Input-output for management control: the case of GlaxoSmithKline, Econ. Syst. Res. 14 (2002) 245–256.

[26] R. Parajuli, T. Dalgaard, U. Jørgensen, A.P.S. Adamsen, M. Trydeman Knudsen, M. Birkved, M. Gylling, J.K. Schjørring, Biorefining in the prevailing energy and materials crisis: a review of sustainable pathways for biorefinery value chains and sustainability assessment methodologies, Renew. Sustain. Energy Rev. 43 (2015) 244–263.

[27] A.J. Ragauskas, C.K. Williams, B.H. Davison, G. Britovsek, J. Cairney, C.A. Eckert, et al., The path forward for biofuels and biomaterials, Science 311 (2006) 484–489.

[28] A.J. Ragauskas, Biorefining and beyond, Biofuels, Bioprod. Bioref. 2 (2008) 199–200.

[29] Rajni Hatti-Kaul, Ulrika Tö rnvall, Linda Gustafsson, Pa°l Bö rjesson. Industrial biotechnology for the production of bio-based chemicals – a cradle-to-grave perspective. Trends in Biotechnology, 25(3): 119–124.

[30] F. Ramirez, A. Seco, Minimizing the environmental effects caused by the production of bioenergy, Renew. Sustain. Energy Rev. 15 (2011) 3327–3331.

[31] R. Roelant, F. Cavani, Integrated biorefineries in the European landscape, in: Joint Biorefinery Conference, Brussels, Belgium, February 11–12, 2014.

[32] B. Sharma, R.G. Ingalls, C.L. Jones, A. Khanchi, Biomass supply chain design and analysis: basis, overview, modeling, challenges, and future, Renew. Sustain. Energy Rev. 24 (2013) 608–627.

[33] Sophia Liu Zhengzhou Qiangjin Science And Technology Trading Co., Ltd, Price for H_2O_2, 2016. Available at: https://www.alibaba.com/product-detail/Hydrogen-Per-oxide-Price-Hydrogen-Peroxide_60341621879.html.

[34] L. Staffas, M. Gustavsson, K. McCormick, Strategies and policies for the

bioeconomy and bio-based economy: an analysis of official national approaches, Sustainability 5 (2013) 2751–2769.

[35] S. Suh, S. Nakamura, Five years in the area of input-output and hybrid LCA, Int. J. LCA 12 (2007) 351–352.

[36] V. Tellarini, F. Caporali, An input/output methodology to evaluate farms as sustainable agroecosystems: an application of indicators to farms in central Italy, Agric. Ecosyst. Environ. 77 (2000) 111–123.

[37] J.B. van Beilen, Transgenic plant factories for the production of biopolymers and platform chemicals, Biofuels, Bioprod. Bioref. 2 (2008) 215–228.

[38] W.N.R. Wan Isahak, Mohamed W.M. Hisham, Mohd AmbarYarmo, Taufiq-yap Yun Hin, A review on bio-oil production from biomass by using pyrolysis method, Renew. Sustain. Energy Rev. 16 (2012) 5910–5923.

[39] T. Wiedmann, M. Lenzen, K. Turner, J. Barrett, Examining the global environmental impact of regional consumption activities — Part 2: review of input–output models for the assessment of environmental impacts embodied in trade, Ecol. Econ. 61 (2007) 15–26.

[40] T. Wiedmann, J. Minx, J. Barrett, M. Wackernagel, Allocating ecological footprints to final consumption categories with input–output analysis, Ecol. Econ. 56 (2006) 28–48.

[41] D.M. Yazan, A.C. Garavelli, A. Messeni Petruzzelli, V. Albino, The effect of spatial variables on the economic and environmental performance of bioenergy production chains, Int. J. Prod. Econ. 131 (2011) 224–233.

[42] D.M. Yazan, I. van Duren, M. Mes, S. Kersten, J. Clancy, H. Zijm, Design of sustainable second-generation biomass supply chains, Biomass Bioenergy 94 (2016) 173–186.

[43] F. You, L. Tao, D.J. Graziano, S.W. Snyder, Optimal design of sustainable cellulosic biofuel supply chains: multiobjective optimization coupled with life cycle assessment and input output analysis, Process Syst. Eng. 58 (2012) 1157–1180.

[44] European Commission, Circular Economy Strategy, Available at, http://ec.europa.eu/smart-regulation/impact/planned_ia/docs/2015_env_065_env+_032_circular_economy_en.pdf, 2015.