Industrial symbiosis for greener horticulture practices: the CO₂ enrichment from energy intensive industrial processes

B. Marchi a,*, S. Zanoni a, M. Pasetti b

a Department of Mechanical and Industrial Engineering, Università degli Studi di Brescia, via Branze 38, Brescia 25123, Italy
b Department of Information Engineering, Università degli Studi di Brescia, via Branze 38, Brescia 25123, Italy

* Corresponding author. E-mail address: b.marchi@unibs.it

Abstract

Carbon dioxide (CO₂) enrichment in controlled environmental conditions has proved to enhance the growth and production of a wide variety of crops. Previous studies suggested that the use of this horticulture practice in greenhouses may represent a useful opportunity for the capture and utilization of industrial CO₂ emissions. The symbiosis among industrial installations and horticulture facilities may in fact allow to reduce the overall amounts of CO₂ released in the atmosphere, by reusing the direct production of carbon dioxide into crop enrichment processes. The present study provides a quantitative analysis of the economic benefits related to the use of CO₂ emissions generated by an industrial activity into a nearby greenhouse facility. The analysis takes into account the savings related to the reuse of carbon emissions from the industrial process, and the additional revenues due to the increase of the yield of products from the horticulture activity. Since the results of the enrichment process strictly depend on the specific crop, the analysis was conducted by comparing three different cultivations, viz. tomatoes, cucumbers and strawberries. The outcomes showed that, for the considered case study, the total benefits related to the implementation of the symbiosis network could reach up to 8.1 € per square meter of cultivated soil per each production cycle, and would also allow to capture up to the 21 % of the overall carbon dioxide emissions produced by the industrial process.

Keywords: Industrial symbiosis; greenhouse horticulture; carbon capture utilization; CO₂ enrichment;

1. Introduction

The greenhouse horticulture is one of the most intensive processes in agricultural practices. This process introduces several improvements with respect to traditional growing techniques. Greenhouses processes, in fact, allow better results in terms of both productivity, higher yield per square meter, and better quality of products, thanks to the more accurate control of growing conditions [1]. Nevertheless, greenhouse processes consume a considerable amount of energy and resources, which generally involve the use of non-renewable sources [1]. For this reason, several research streams have been investigated, including sustainable greenhouse horticulture, reduction of water usage, and advanced plant breeding.

One of the most relevant issues in greenhouse processes concerns the control methods and instruments used to keep specific indoor conditions, such as air humidity, vertical temperature gradients, and carbon dioxide (CO₂) concentration. In particular, the accurate control of CO₂ concentration plays a relevant role in crop production. Recent studies, in fact, showed that the increase of CO₂ concentration in greenhouses– also known as CO₂ enrichment – is capable to enhance the grow rate of plants, by increasing the activity of nitric oxide synthase in roots [2], thus leading to the increase of production yields [3]. This effect has been confirmed in most greenhouse crops, where the net photosynthesis process has shown to vary by following the increase of CO₂ concentration. Generally, when raising the CO₂ concentration from typical ambient values, i.e. about
Industrial symbiosis is implemented when traditionally was introduced by Chertow in 2000 [8], who stated that the synergy among energy-intensive processes and the greenhouse horticulture. CO2 enrichment in greenhouse applications is the combustion of CO2 emissions (e.g. an energy-intensive factory that produces large amounts of CO2 emissions) is connected to the greenhouse through pipeline networks. In this scenario, the CO2 enrichment in horticultural applications would thus represent a potential Carbon Capture and Utilisation (CCU) method, which could also provide a cost-effective and environmental friendly alternative to the combustion of fossil fuels in greenhouses. The reuse of almost pure emissions in greenhouse cultures from factories located in the direct neighborhood, would then allow the reduction of the CO2 emissions for both the industry and the greenhouse horticulturists.

Different studies, such as [6], [7], and [4], observed that the synergy among energy-intensive processes and greenhouses, including the exploitation of CO2 emissions for the enrichment of greenhouse cultivations, could increase the revenues and the process efficiency of the symbiotic network. However, a systematic and quantitative evaluation of these benefits haven’t been proposed by the scientific literature, although such studies could provide practical and relevant information to investors and policy makers for the development and implementation of synergy actions. The aim of the present work is to present a quantitative analysis of the economic benefits related to the exploitation of CO2 emissions from industrial processes for the enrichment of greenhouse cultivations. The study was conducted by evaluating the reduction of costs related to the reduction of carbon emissions in an energy-intensive industrial process, and the increase of revenues in a nearby greenhouse facility, due to the increase of the yield of products through CO2 enrichment.

The remainder of the paper is organized as follows: in Section 2 the theoretical background of the study is presented, providing insights on the main topics of the paper, viz. on the concept of industrial symbiosis and on the use of horticulture applications as CCU methods for energy-intensive processes. Section 3 describes the case study considered in the present work, while Section 4 defines the model used to compute the economical benefits of the industrial symbiosis among CO2 enrichment in horticulture and industrial processes. Section 5 provides the numerical results of the proposed analysis for the considered case study. Finally, Section 6 summarizes the main findings of the study and provide suggestions for future research.

2. Theoretical background

2.1. Industrial symbiosis: the concept

The most common concept of industrial symbiosis (IS) was introduced by Chertow in 2000 [8], who stated that industrial symbiosis is implemented when traditionally separate entities are involved in a collective approach, to create competitive advantages and to produce economic, environmental and social benefits for all the involved firms. Industrial symbiosis also brings the attention to closed-loop solutions and circular economies, for which nothing is destroyed and no waste and pollution are produced, but everything is recycled or re-used. The key principle of IS consists in the exploitation of collaborative synergies offered by the geographic proximity among different subjects, that can be both private companies and public organizations [9]. These opportunities can be grouped into three main transactions: (i) by-product exchanges, in which waste are used as raw material in input to other actors, (ii) infrastructures, utilities or access to services (such as energy or waste treatment) sharing, and (iii) cooperation on issues of common interest, such as emergency planning, training or sustainability planning [10].

2.2. Carbon Capture and Utilization: the symbiotic potential among horticulture and energy-intensive processes

According to [11], the direct CO2 emissions of industrial activities are responsible for almost the 21% of global CO2 worldwide emissions. This is a quite impressive fact, if we consider that it doesn’t take into account the indirect emissions due to the consumption of electrical power by industrial processes. For this reason, local governments and global organizations are looking at cost-efficient ways to reduce carbon emissions from industrial activities. Among these, Carbon Capture and Storage (CCS) and CCU have been recognized as effective practices for the reduction of CO2 emissions in energy-intensive manufacturing industries [6].

Table 1. Direct CO2 emissions by industrial activity of worldwide large stationary CO2 sources with emissions of more than 0.1 million tons of CO2 (MtCO2/y) per year [11].

<table>
<thead>
<tr>
<th>Process</th>
<th>CO2 emissions (MtCO2/y)</th>
<th>Percentage of global CO2 emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power generation</td>
<td>4492</td>
<td>33.4 %</td>
</tr>
<tr>
<td>Cement production</td>
<td>932</td>
<td>6.9 %</td>
</tr>
<tr>
<td>Refineries</td>
<td>798</td>
<td>5.9 %</td>
</tr>
<tr>
<td>Iron and steel industry</td>
<td>646</td>
<td>4.8 %</td>
</tr>
<tr>
<td>Petrochemical industry</td>
<td>379</td>
<td>2.8 %</td>
</tr>
<tr>
<td>Global CO2 emissions</td>
<td>13466</td>
<td>100 %</td>
</tr>
</tbody>
</table>

The use of horticulture as CCU method for the mitigation of carbon emissions in energy-intensive processes is already a mature technology. Recent studies, such as those of ref. [4] and [6], estimated that the potential CO2 utilization by horticulture applications in Europe could reach up to 22 million tons of CO2 per year (MtCO2/y). However, only few applications of CCU through horticulture have been launched, most of which mainly at research or demonstration stage [12]. In addition, the actual cost effectiveness of this application is still uncertain, because it depends on several factors, such as the CO2 concentration required by the enrichment process, the degree of contamination of industrial gas streams, and daily and seasonal variations of CO2 supply. A comprehensive
economic evaluation that would consider all of these factors is still absent in the literature. Few studies, such as that presented in [7], proposed technical evaluations or experimental results for specific case studies, but it didn’t consider economical aspects.

3. Case study

In this study, we considered the industrial symbiosis potential between an energy-intensive factory that makes use of forging processes, and a nearby greenhouse installation of about 100,000 m² of cultivated area. The considered industrial installation is represented by an existing factory located in Brescia, Italy, characterized by a CO₂ production of 9,314 tCO₂/y. CO₂ emissions in the forging process are mainly produced by the reheating furnaces in which the ingots are heated for reaching the process temperature.

The considered industrial process is particularly suitable for the application of carbon capture and utilization through horticulture enrichment. Firstly, the properties of the process exhausts (such as the level of contaminants, and the temperature) match the requirements of the CO₂ horticulture enrichment. Secondly, the close proximity to an existing greenhouse installation allows the direct transportation of CO₂ through pipelines.

Table 2. Characteristic parameters of the crops considered in the case study. Yield data is reported as kg of crop products per square meter of cultivated area, per each production cycle. Data was derived from ref. [1], [14] and [15].

<table>
<thead>
<tr>
<th>Crop</th>
<th>Tomato</th>
<th>Cucumber</th>
<th>Strawberry</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ enrichment [kg/m²]</td>
<td>16</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>CO₂ concentration [ppm]</td>
<td>800-1000</td>
<td>600-800</td>
<td>700-1000</td>
</tr>
<tr>
<td>Increased production due to CO₂ enrichment</td>
<td>30 %</td>
<td>35 %</td>
<td>38.5 %</td>
</tr>
<tr>
<td>Production yield at standard conditions [kg m⁻² cycle⁻¹]</td>
<td>42</td>
<td>58</td>
<td>7</td>
</tr>
<tr>
<td>Crop price [€/kg]</td>
<td>0.56</td>
<td>0.39</td>
<td>1.62</td>
</tr>
</tbody>
</table>

In this study, we considered the cultivation of three different crops in the greenhouse installation, viz. tomatoes, cucumbers, and strawberries. The main characteristic parameters used in the quantitative analyses for each selected culture are reported in Table 2.

In order to better evaluate the actual benefits (i.e. savings and additional revenues) deriving from the exploitation of this industrial symbiosis network, the proposed system was compared to two different scenarios (namely Scenario A and B), as described in the following.

3.1. Scenario A: Traditional system without CO₂ enrichment

This scenario considers the case of a traditional greenhouse installation. This system represents the AS-IS scenario, in which the production of the crops is not enhanced by CO₂ enrichment and the heating of the greenhouse is provided by burning heaters using natural gas (Fig. 2a). In this case, there aren’t additional revenues deriving from the CO₂ enrichment of plants. Moreover, since the carbon dioxide emission of the forging process are not recovered through the CCU application, additional costs due to the application of carbon taxes must be taken into account.

3.2. Scenario B: Traditional system with CO₂ enrichment

This scenario considers the case of a traditional greenhouse installation that makes use of CO₂ enrichment methods for the cultivation of crops, without exploiting the industrial symbiosis potential for the supply of CO₂ (Fig. 2b). In this case, the CO₂ enrichment in the greenhouse is achieved by burning additional natural gas by means of existing heaters (about 0.23 kgCO₂ are provided per kWh of burned gas). This scenario accounts for additional costs (i.e. additional natural gas is burned for the enrichment process), but also produces additional revenues, thanks to the increase of the crop production. In this case, as in Scenario A, the CO₂ emissions produced by the forging process are not recovered, thus accounting for additional costs due to carbon taxes.

3.3. Scenario C: The industrial symbiosis network

Scenario C represents the exploitation of the industrial symbiosis network among the forging process and the carbon enrichment technique of the greenhouse installation. In this
scenario, the two companies (i.e. the factory and the agricultural activity) cooperate with the aim of improving the environmental and economic performances of the overall system.

For the considered case study, the use of CO₂ emissions from the industrial process leads to three different economic benefits: (i) the increase of revenues, thanks to the increase of the crop production by using the recovered CO₂ through plant grow enrichment, (ii) the reduction of costs related to CO₂ emissions of the industrial process (emissions are reduced by the quantity of CO₂ used in the enrichment process), and (iii) the reduction of costs due to the non-utilization of natural gas for the production of CO₂ in the greenhouse.

4. Economic model

In the following, the economic model used in the present works is described in detail. The evaluation of the economic benefits related to the implementation of the symbiosis network (Scenario C), compared to the non-symbiotic system of Scenario A, was carried out by computing the additional benefits ΔπA that can be accounted for the former:

$$\Delta \pi_A = \pi C \Delta Y_C / S_C + c_{CO₂} Q_{EC}$$  \hspace{1cm} (1)

where \(\pi C\) is the selling price of the considered crop (€/kg), \(\Delta Y_C\) is the yield increment due to the CO₂ enrichment process (%), \(S_C\) is the production yield in standard conditions (i.e. without CO₂ enrichment), expressed in kg m⁻² cycle⁻¹, \(c_{CO₂}\) is the carbon tax due to CO₂ emissions from the industrial process (€/kgCO₂), and \(Q_{EC}\) is amount of CO₂ required by the enrichment process for the given crop per each production cycle (kgCO₂ m⁻² cycle⁻¹). The additional benefits \(\Delta \pi_A\) are thus expressed as specific benefits per square meter of cultivated crop, per each production cycle (€ m⁻² cycle⁻¹).

On the other hand, if we compare the implementation of the symbiosis network (Scenario C) with the traditional greenhouse horticulture with CO₂ enrichment (Scenario B), the additional benefits \(\Delta \pi_B\) related to the symbiosis network will account only for the savings due to the avoided consumption of natural gas for the production of the CO₂ quota required by the enrichment process:

$$\Delta \pi_B = c_G Q_{EC} / \gamma + c_{CO₂} Q_{EC}$$ \hspace{1cm} (2)

where \(\gamma\) is the amount of CO₂ produced by burning the equivalent energy content of natural gas (equal to 0.23 kg/kWh), and \(c_G\) is the cost of the natural gas supply per equivalent energy content (€/kWh). As for \(\Delta \pi_A\), the additional benefits \(\Delta \pi_B\) are expressed as specific benefits per square meter of cultivated crop, per each cycle (€ m⁻² cycle⁻¹). In this study, the cost of natural gas supply \(c_G\) was set to 0.05 €/kWh.

The values of the crop price \(\pi C\), of the relative increase of crop production \(\Delta Y_C\), of the standard production yield \(S_C\), and of the amount of CO₂ enrichment \(Q_{EC}\), for each considered crop, can be found in Table 2.

5. Results and discussion

The economic benefits related to the implementation of the industrial symbiosis network (namely Scenario C) was computed with respect to the non-symbiotic systems described in Section 3 (namely Scenarios A and B), by using the economic model described in Section 4. The results, reporting the additional benefits (viz. the sum of additional revenues and savings) of Scenario C with respect to Scenarios A and B are reported, respectively, in Table 3 and Table 4.

It’s worth to note that the number of production cycles during each year depends on the specific crop, and may also depend on other factors, including fluctuations of the market demand and specific production plans operated by each producer. For this reason, a proper comparison of different crops should be conducted over a given time period, taking into account the different number of production cycles. However, since the crops considered in this study are characterized by nearly equivalent number of cycles per year, the results presented in this study can be directly used to compare the related economic benefits.

Table 3. Economic benefits related to the implementation of the industrial symbiosis network, compared to a traditional (i.e. non-symbiotic) system without CO₂ enrichment (namely Scenario A). Results are reported in € per square meter of cultivated area, per each production cycle (€ m⁻² cycle⁻¹).

<table>
<thead>
<tr>
<th>Crop</th>
<th>Revenues due to CO₂ enrichment process</th>
<th>Savings due to the reduction of CO₂ emissions</th>
<th>Total benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomato</td>
<td>7.056</td>
<td>0.112</td>
<td>7.168</td>
</tr>
<tr>
<td>Cucumber</td>
<td>7.917</td>
<td>0.14</td>
<td>8.057</td>
</tr>
<tr>
<td>Strawberry</td>
<td>4.366</td>
<td>0.105</td>
<td>4.471</td>
</tr>
</tbody>
</table>

Table 4. Economic benefits related to the implementation of the industrial symbiosis network, compared to a traditional (i.e. non-symbiotic) system which makes use of CO₂ enrichment methods (namely Scenario B). Results are reported in € per square meter of cultivated area, per each production cycle (€ m⁻² cycle⁻¹).

<table>
<thead>
<tr>
<th>Crop</th>
<th>Savings due to the reduction of gas consumptions</th>
<th>Savings due to the reduction of CO₂ emissions</th>
<th>Total benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomato</td>
<td>3.478</td>
<td>0.112</td>
<td>3.590</td>
</tr>
<tr>
<td>Cucumber</td>
<td>4.348</td>
<td>0.14</td>
<td>4.488</td>
</tr>
<tr>
<td>Strawberry</td>
<td>3.261</td>
<td>0.105</td>
<td>3.366</td>
</tr>
</tbody>
</table>

The results show that, for the considered case study, the exploitation of the industrial symbiosis network defined in Scenario C would lead to economic benefits between 340 and 800 €/cycle. Within the three different crops, the cultivation of cucumbers presented the highest economic benefits in both the considered comparisons (viz. Scenario C vs. A and vs. B), varying from 4.5 to 8.1 € m⁻² cycle⁻¹, while the cultivation of strawberries presented the lowest, ranging from 3.4 to 4.5 € m⁻² cycle⁻¹. The lower economic benefits in the case of strawberry crops can be attributed to the poor production yield at standard conditions, which is almost an order of magnitude lower than that of cucumbers and tomatoes.

For the considered scenarios, the exploitation of the industrial symbiosis network lead to better results if applied to a traditional horticulture systems without CO₂ enrichment.
This is due to the higher additional revenues introduced by the CO₂ enrichment process, compared to the savings from the avoided consumption of natural gas in existing greenhouses which already use that horticulture technique.

It is worth to note that, for the considered case study, the exchange of CO₂ among the forging process and the greenhouse installation would allow to recover from 1,500 to 2,000 tons of CO₂ per cycle, which represent from 16 % to 21 % of the overall carbon dioxide emissions of the considered industrial installation. However, the economic contribution due to existing emission trading schemes is almost negligible if compared to the effects related to the increase of crop production (see Fig. 3) or to the savings from avoided gas consumption (see Fig. 4). Nevertheless, this represent a relevant fact, that could be taken into consideration by policy makers when evaluating possible incentive schemes for the implementation of symbiotic networks between energy-intensive industrial processes and greenhouse installations.

6. Conclusions

In this study, we evaluated the economic benefits of the exploitation of symbiotic networks between energy-intensive industrial processes and greenhouse horticulture installations. The analysis was conducted by computing the additional revenues and savings due to the use of the symbiotic network with respect to two non-symbiotic systems: a traditional greenhouse installation without CO₂ enrichment, and a comparable system which makes use of CO₂ enrichment techniques. The analysis was carried out by considering two existing installations (viz. an energy-intensive industrial process which produces 9.3 tCO₂/y, and a nearby greenhouse system with 100,000 m² of cultivated soil), for three different crops, namely: tomatoes, cucumbers and strawberries. The analysis takes into account three different economic contributions: the increase of revenues deriving from the CO₂ enrichment process, the savings due to avoided natural gas consumptions (used in traditional CO₂ enrichment methods), and savings due to the reduction of CO₂ emissions in the industrial installation.

The results showed that, for the considered case study, the implementation of the industrial symbiosis network would lead to economic benefits between 0.68 and 1.6 M€/year, assuming 2 production cycles per year, which corresponds to the typical cultivation schedules for the selected crops. The best results are achieved in the case of a symbiotic network with a traditional greenhouse system without CO₂ enrichment, which led to almost twice the economic benefits, with respect to greenhouse systems making use of CO₂ enrichment techniques. In both the cases, the economic contribution due to the reduction of CO₂ emissions in the industrial process is almost negligible if compared to the effects related to the increase of crop production or to the reduction of natural gas consumption. Nevertheless, this represents a relevant fact, that should be taken into consideration by policy makers for possible funding schemes on the matter.

The symbiotic potential among energy-intensive processes in industry and horticulture activities could also be exploited by implementing the heat recovery of process exhausts for the heating of greenhouses installations. The evaluation of the economic benefits deriving from that synergy has not been considered in the present analysis, which has focused only on the CO₂ exchange potential, but represents a relevant topic that should be addressed by further studies.

Although the present study offered a first order evaluation of the potential economic benefits – viz. the increase of revenues and savings – of the CO₂ enrichment in horticulture from industrial processes, a comprehensive Life Cycle Cost (LCC) analysis would be required to better estimate the economic feasibility of this application. Furthermore, since the implementation of symbiotic networks among industrial processes and horticulture activities would require the use of raw materials, as well as construction and transportation activities, thus accounting for additional energy consumption and GHG emissions, a detailed Life Cycle Assessment (LCA) analysis must be carried out for the proper evaluation of its energy and environmental sustainability.
References


