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Toward Net Zero Emissions: Sustainable Design of a Supply Chain for the Revalorization of CO_2 in Mexico

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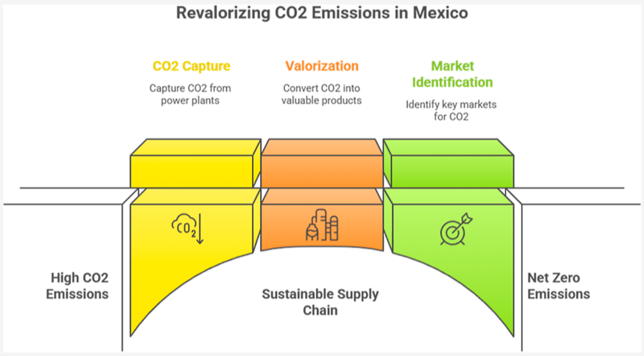
ABSTRACT: Electricity generation is a significant source of global CO_2 emissions, accounting for around 40% of total emissions. This paper presents a sustainable supply chain model aimed at capturing and revalorizing CO_2 emissions from fossil-fueled power plants in Mexico, aligning with Sustainable Development Goals (SDGs). The model incorporates early CO_2 capture technologies, like amines, and more advanced technologies, like deep eutectic solvents (DES), and identifies key markets for valorization, including methanol production, urea synthesis, fuel generation, and enhanced oil recovery. Formulated as a mixed-integer linear programming (MILP) problem, the model seeks to maximize net profit and job creation while minimizing environmental impact. Two critical metrics analyzed are total social welfare (TSW) and net emissions balance. The optimal solution yields a profit of USD 179.35 per ton of captured CO_2, an environmental impact score of 71.57 points per ton, and a net negative emissions balance of −0.19 tons of CO_2 per ton captured. Additionally, it creates over 55,000 jobs annually and achieves a TSW score of 10.63, meeting about 75% of market demand. This research underscores the potential of CO_2 capture and revalorization in promoting economic growth and environmental sustainability. Further research is needed to enhance market satisfaction and scalability.



■ INTRODUCTION

Today, global warming has reached alarming levels, representing one of the most important challenges of our time. This devastating phenomenon, generated mainly by the uncontrolled accumulation of greenhouse gases, is triggering a series of negative impacts on our planet. Among these gases, carbon dioxide (CO_2), whose emissions have increased significantly due to human activity, stands out. According to data provided by the International Energy Agency, in 2021, the total CO_2 emission was almost 35,000 Mt of CO_2.[1] The main contributors to these emissions were the electricity generation sector, with 14,644.3 Mt of CO_2, followed by the industrial sector with 6,341 Mt of CO_2, and the transportation sector with 7,631.5 Mt of CO_2. This represents approximately 42%, 18% and 22% respectively of total emissions.[1]

In Mexico, the situation with respect to CO_2 emissions is equally alarming, registering emissions equivalent to 456 million tons in the same period.[2] It is relevant to highlight that the electricity sector is the main contributor to these emissions at the national level, representing approximately 36.7% of the total, followed by the transport fuel sector with 32.0%, and then industrial processes with 10.2%.[2] This situation underlines the urgency of adopting more sustainable and cleaner energy measures at both global and national levels.

Given this reality, CO_2 capture and reuse have emerged as critical areas of interest, driving research into various methods and processes to accomplish these tasks.

CO_2 capture technologies are divided into three main types: precombustion capture, postcombustion capture and oxygen combustion technology. Precombustion capture and combustion capture with oxygen require specific materials and stringent high temperature conditions, which limits their application.[3] In contrast, postcombustion capture is widely used in the industry due to its maturity and efficiency.[3] In the context of the 2030 agenda, CO_2 capture aligns closely with several Sustainable Development Goals (SDGs), such as SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 13 (Climate Action) and SDG 14 (Undersea Living), among others.[4]

Worldwide, CO_2 capture plants are already operating in countries such as Canada, Norway and the United States, with

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their main applications being enhanced oil recovery and geological storage beneath the ocean.[5−8] However, the CO_2 capture and utilization are not new, since the early 2010s, large-scale recycling of CO_2 emitted by human activities has been proposed, mainly by producing synthetic fuels and chemicals based on physical-chemical approaches,[9] by using renewables or nuclear energy to carry out CO_2 captured and H_2O dissociation methods such as thermolysis, thermochemical cycles, electrolysis and photo electrolysis.[10,11] The deployment of renewable energies has been key to enabling the reuse of captured CO_2 and not just limiting it to storage, by technologies power to gas and power to liquids.[12] These experiences demonstrate that capture technologies are technically viable and strategically relevant. However, beyond storage, the valorization of captured CO_2 represents a crucial step for climate change mitigation and the transition toward a low-carbon economy. In technical terms, its importance lies in several reasons.

- Converting captured CO_2 into useful products contributes to reducing net carbon emissions, thus avoiding its release into the atmosphere and promoting its application in beneficial processes.
- By integrating captured CO_2 into industrial processes or in the production of materials, the circular economy is promoted, improving resource efficiency and reducing dependence on nonrenewable raw materials.
- Captured CO_2 can be used as raw material in the production of various sustainable products and materials, such as synthetic fuels, chemicals, construction and agricultural materials, thus reducing its environmental impact and contributing to the sustainability of various industrial sectors.
- Using captured CO_2 in the production of durable products, such as building materials or chemicals, can be effectively stored in the long term, preventing its gradual release into the atmosphere.
- CO_2 valorization can generate economic opportunities by creating new carbon-based markets and products, supported by economic incentives such as carbon pricing or carbon credits, making it economically viable and attractive to businesses and society in general.

There are several potential uses for CO_2 from capture processes, Ho and Iizuka presented a wide range of CO_2 utilization pathways, with and without purification and pressurization, and with direct use and by conversion.[13] In general, in this study we consider two broad categories for CO_2 utilization: direct use and conversion. In direct use, it is used as an enhancer in greenhouses, algae cultivation and in the production of fertilizers and urea. It also has direct applications in the food sector, medical uses and as a solvent. On the other hand, in the conversion markets, the production of chemicals of interest, the production of fuels and its use in construction materials stand out.[14] Among the most innovative applications are e-fuels, synthetic fuels obtained from green hydrogen and CO_2 via the Fischer−Tropsch process.[15,16] These e-fuels include a variety of fuels, among which gasoline, diesel and turbosine are the most important.[16] These are conventional fuels widely used in the transportation sector, which facilitates their integration into existing infrastructure and technologies, offering a smoother transition to more sustainable energy options. The most outstanding feature of these synthetic fuels is that they promise to be virtually carbon neutral, as the carbon dioxide used in their production is almost equivalent to that released during combustion.[15]

Within the circular economy, supply chain design plays a pivotal role in enabling the efficient integration of CO_2 capture and utilization. A well-structured supply chain ensures resource optimization, promotes circular practices, reduces environmental impact through efficient production and renewable energy use, and enhances competitiveness by lowering costs, improving efficiency, and meeting the growing demand for sustainable products. Moreover, it opens new market opportunities while consolidating corporate reputation. Previous studies on supply chain design have highlighted the importance of evaluating solutions not only through economic metrics such as net profit, but also through social indicators such as job creation, and environmental indicators such as eco-indicator 99 and water footprint.[17,18] In the specific context of carbon dioxide capture, in recent years, the supply chain approach has become a key strategy for decarbonization and CO_2 mitigation, focusing primarily on the quantification, optimization and mitigation of emissions.[19−21] In Europe, initial contributions considered CO_2 capture and storage as a decarbonization pathway for carbon-intensive sectors such as steel, cement, and refining.[22−24] Later, Galán et al.[25] proposed a multiscale analysis for CO_2 capture and utilization in Spain, focusing on its conversion into methane and methanol. Their work emphasized the advantages of amine-based (MEA) capture over direct air capture, as well as the higher potential of methanol production compared to methane. Similarly, Ostovari et al.[26] investigated the large-scale potential for greenhouse gas reduction through CO_2 mineralization, proposing an optimal supply chain that integrates capture, mineralization, and transportation, while accounting for life cycle emissions. Complementarily, Leonzio and Zondervan[27] showed that between 40% and 80% of CO_2 emissions could be reduced in Germany by profitably transforming captured carbon into value-added products such as methanol, dimethyl ether, formic acid, acetic acid, urea, and polypropylene carbonate. Other studies have addressed other case studies such as Asia and North America.[28,29]

In this context, this paper focuses on the problem of carbon dioxide emissions in Mexico by designing a supply chain that captures and revalorizes carbon dioxide as a raw material to produce value-added products. Although CO_2 capture is technically feasible and necessary in several industries, the cost of the capture process limits it to large-scale industries such as power generation, steel, and cement.[30,31] In Mexico, the latter two industries belong to the private sector and already have initiatives for CO_2 capture and mitigation, while power generation is controlled by the state and there are no initiatives or progress in this regard, so this work focuses on power generation plants.

A key aspect is that the proposed supply chain will integrate two capture technologies and direct the revalorization of carbon dioxide to domestic markets, taking as a case study electricity generation in Mexico. The performance of this supply chain will be evaluated through various metrics, which will make it possible to measure its impact and its contribution to meeting the goals of the 2030 Agenda, thus promoting a comprehensive solution for reducing emissions.

The Problem of CO_2 Emissions in Electricity Generation in Mexico. In Mexico, the *Comisión Federal de Electricidad* (CFE) is responsible for generating and supplying electricity. In 2022, approximately 60% of the energy was

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produced by fossil fuel technologies, while the remaining 40% corresponds to the use of clean energies.[32] The fossil technologies that contribute most to electricity generation are conventional thermoelectric and combined cycle thermoelectric with approximately 50% of national generation.[32,33] Electricity production in these two technologies is mainly produced using natural gas as fuel, so electricity generation involves carbon dioxide emissions from the burning of this fuel.[33] According to data provided by the CFE, its thermoelectric plants produce about 0.7 tons of carbon dioxide for each MWh produced,[33] in this sense, the emissions associated with each thermoelectric plant were calculated using this factor. Table 1 shows the locations of the thermoelectric plants, as well as their capacity and associated emissions.

Table 1. Conventional and Combined Cycle Thermoelectric Power Plants in Mexico[32,33]

	Conventional		Combined Cycle	
State	Capacity (MW)	E_j (Mton/year)	Capacity (MW)	E_j (Mton/year)
Baja California	320	1.962	743	4.556
Baja California Sur	113	0.692		
Campeche	113	0.692		
Chihuahua	616	3.777	1,141	6.996
Colima	1,300	7.971	1,454	8.915
Durango	320	1.962	240	1.471
Estado de México			1,288	7.898
Guanajuato	550	3.372		
Hidalgo	1,606	9.847	594	3.642
Morelos			656	4.022
Nuevo León			849	5.206
Puebla			382	2.342
Querétaro			591	3.624
San Luis Potosí	700	4.292		
Sinaloa	936	5.739		
Sonora	632	3.875	2,281	13.987
Tamaulipas	800	4.905	211	1.293
Veracruz	1,750	10.731	458	2.808
Yucatán	243	1.490	220	1.349
Total	**9,998**	**61.307**	**11,108**	**68.109**

To address the problem of carbon dioxide emissions in Mexico due to the generation of electricity through conventional and combined cycle technologies, we propose the implementation of a supply chain that will allow the capture and revalorization of this compound. The proposed supply chain consists of installing the capture technologies (i) in the two types of thermoelectric plants (j) with the purpose of capturing the emissions associated with the generation of electricity, subsequently the carbon dioxide captured by the technologies (i) will be distributed to the markets (m) for its revalorization in the production of compounds of interest. The design problem of the supply chain consists of selecting the capture technology i to be installed in each thermoelectric plant j, this will depend on the requirements of each market m. Once technology i has been installed and the carbon dioxide has been captured, the delivery arc corresponding to the distance between thermoelectric plant j and market m is selected.

Supply Chain Considerations. In recent years, research on capture technologies has focused on scaling up postcombustion technologies toward industrialization, demonstrating high capture efficiencies. Some of these studies have employed aqueous amine solutions[34] or deep eutectic liquids.[35] These technologies achieve capture efficiencies above 99%. However, a notable difference in the purity of the captured carbon dioxide is evident between the two methods: while amine solutions achieve a purity of 99 wt %, the use of deep eutectic liquids results in a purity of approximately 95 wt %.[34,35] On the other hand, in environmental and economic issues it has been reported that deep eutectic liquids show a lower environmental impact and a higher total annual cost with respect to amine technology.[35]

The selection of markets for captured CO_2 was intended to be broad but within the context of the country's industry. Since Mexico is a country with several oil wells from which this raw material is extracted for further processing, it is expected that the main uses of postcapture carbon dioxide will be for enhanced oil recovery. E-fuels from the Fischer–Tropsch process and methanol were also selected due to the trends of e-fuels production. Particularly in the case of methanol, in Mexico, exist a project to produce e-methanol under the Mexinol brand, so this study considers the evaluation to supply CO_2 to this process. Methanol production from captured CO_2 has been widely recognized as one of the most extensively studied routes for CO_2 valorization.[36] Several works have focused on describing the process and its operating conditions,[37,38] as well as proposing novel simulation-based approaches for optimizing CO_2 conversion into methanol.[39] Moreover, the integration of methanol synthesis with different CO_2 capture technologies has been investigated, highlighting that the capture stage significantly influences the overall production cost.[37] Amine-based capture processes coupled with catalytic hydrogenation of CO_2 to methanol have attracted increasing attention due to their potential to enhance process efficiency and sustainability.[40] On the other hand, e-methanol supply chain models have been developed for their distribution in Europe; however, these models consider e-methanol as the sole product.[41] These works highlight the importance and growing interest in e-methanol production, both as a final product and as a raw material.

Also, there is considered urea for fertilizer production since Mexico is an agricultural country and has a large market for this fertilizer, and carbonated beverage production since Mexico is the world's leading consumer of soft drinks, with an average of 163 L per person per year.[42] In this sense, after a literature review, carbon dioxide revalorization focuses on 42 potential markets according to the five uses proposed, derived from IEA data, the use of CO_2 by application is reported in Table 2.

Table 2. Uses of Carbon Dioxide

Aplication	Use of CO_2
Urea production[43]	0.60 ton/ton urea
Oil recovery[44]	0.169 ton/barrel
Methanol production[45]	1.27 ton/ton methanol
Fuel production (FT)[46]	26.52 ton/ton naptha
	14.55 ton/ton jet
	24.61 ton/ton diesel
Soft drink production[47]	3.1 g/L soft drink

Figure 1. Demand for CO_2 in ton/year.

The CO_2 demands for each of the applications in million tons per year amounts to approximately 1.130 for urea production,[48,49] 113 for oil production,[50] 3,423 for methanol production,[51,52] 322 for naphtha production,[51] and 0.065 for soft drink production.[53] The geographic location of each market and their respective demand and application are reported in the Supporting Information. PEMEX stands out as the main customer since its product portfolio includes the production of fuel, methanol, petroleum and urea.[51] On the other hand, Mexinol stands out as a future project for methanol production.[52] Figure 1 shows graphically in which states of the country the demand for carbon dioxide is concentrated.

Once the capture technologies and potential uses of CO_2 in Mexico are defined, the supply chain superstructure is generated (Figure 2), which contains 3 layers, thermoelectric plants (j), capture technologies (i) and markets (m). The model consists of 28 thermoelectric plants, 2 capture technologies and 42 markets. Economic, social and environmental objectives will be used to evaluate the performance and sustainability of the supply chain. The model will be posed as a mixed integer linear programming problem (MILP) and solved using the ε-constrain optimization method.

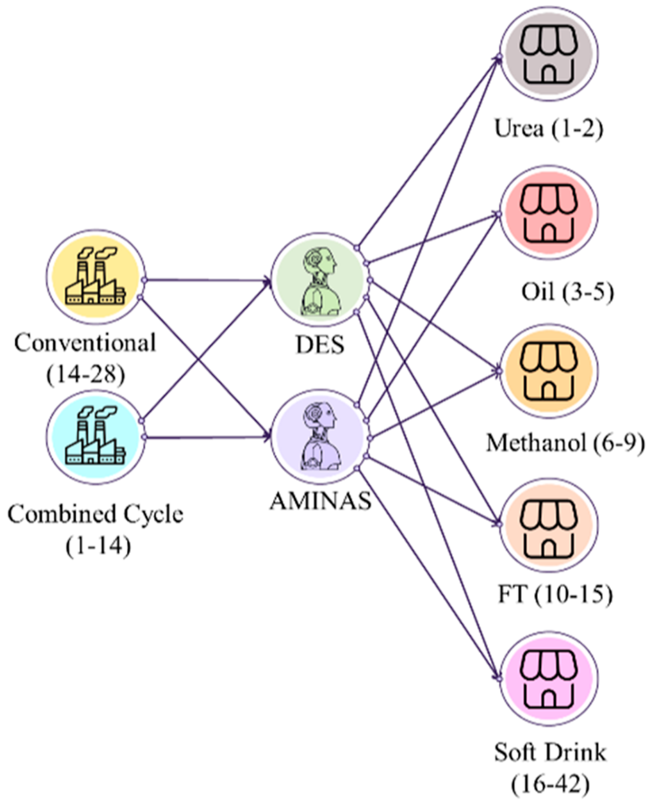

Figure 2. Supply chain superstructure.

Mathematical Model. This section presents the formulation of the mathematical model for the carbon dioxide supply chain. The model developed corresponds to a mixed integer linear programming problem (MILP). For the calculation of the distances between markets and plants, the course line method was used. It is important to note that the chain will be able to make use of two CO_2 capture technologies (amines and DES).

Mass Balances in Thermoelectric Plants. The material balances in each thermoelectric plant, conventional or combined cycle, begin with the quantification of the carbon dioxide captured by the installed capture plant. In this way, the carbon dioxide captured in each plant is defined as

$$\mathrm{CC}_{i,j} = \eta_i \times E_j \times \quad t_{i,j} \qquad \forall\ i,\ j \tag{1}$$

where η_i represents the efficiency of the capture technologies and E_j the CO_2 emissions of each thermoelectric plant considered. In addition, a binary variable ($t_{i,j}$) is created to determine whether a capture plant is installed or not.

Although the technologies considered show high capture efficiency, this is not total, so it is necessary to quantify how much carbon dioxide is not captured (eq 2). In addition, capture technologies also require heating services, so we quantify how much carbon dioxide is emitted by each installed plant (eq 3) by adding a carbon dioxide production coefficient (P_i), which indicates how many tons of CO_2 are produced for each captured ton.

$$\mathrm{CNC}_{i,j} = (1 - \eta_i) \times E_j \times t_{i,j} \qquad \forall\ i,\ j \tag{2}$$

$$\mathrm{CPT}_{i,j} = P_i \times E_j \times t_{i,j} \qquad \forall\ i,\ j \tag{3}$$

Finally, the total carbon dioxide emitted by the installation of a capture plant is calculated, taking into account the carbon dioxide emitted by the services associated with each

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technology and the carbon dioxide not captured due to its efficiency.

$$CE_{i,j} = CNC_{i,j} + CPT_{i,j} \qquad \forall\ i, j \tag{4}$$

Model Constraints. The model considers shipping restrictions by the amount of carbon dioxide captured and demanded. In addition, restrictions by technology are included, due to the characteristics that the product must have for certain markets.

The restriction of thermoelectric plant shipments to markets associated with carbon dioxide capture of product is expressed as follows

$$b^{L} \times y_{j,m} \leq S_{j,m} \leq b^{U} \times y_{j,m} \qquad \forall\ j, m \tag{5}$$

where b^U and b^L represent the upper and lower limits of carbon dioxide captured in thermoelectric plants. $y_{j,m}$ is the binary variable that selects the shipping $j \rightarrow m$ (shipments from thermoelectric plants to markets).

On the other hand, it is also necessary to restrict these shipments to the individual demands of each market, which is represented as

$$DM_m \geq \sum_j S_{j,m} \geq 0 \qquad \forall\ m \tag{6}$$

where DM_m is the vector which contains the demands of all the m markets considered, basically, this restriction tells us that a market cannot receive more product than it demands.

As previously mentioned, the model also includes technology constraints. The first of these is related to the subset of food markets (FM) which require a CO_2 purity of 99%. Such purity is only achieved using capture technology that uses amines as a solvent. This constraint is formulated as follows

$$\sum_m y_{j,FM} \leq \sum_i t_{amines,j} \qquad \forall\ j \tag{7}$$

The last constraint considered restricts the number of technologies used for CO_2 capture at each thermoelectric plant to a single technology, which is represented as

$$\sum_i t_{i,j} \leq 1 \qquad \forall\ i \tag{8}$$

Product Transportation. According to Mexico's Secretariat of Communications and Transportation (SCT), trucks are the main means of transportation for products in Mexico. Based on data provided by the SCT, the costs associated with this type of transportation include fixed costs that depend on the amount of transported product, and variable costs that depend on the distance traveled.[54,55] The equations used to calculate transportation costs in dollars are as follows[55]

$$VTC = 0.0069 \sum_j \sum_m DJM_{j,m} \tag{9}$$

$$FTC = 3.126 \sum_j \sum_m S_{j,m} \tag{10}$$

where $DJM_{j,m}$ is the distance selected for the shipping arc $j \rightarrow m$ and $S_{j,m}$ is the amount of shipped product to the selected markets. Additionally, the emissions associated with the transportation of the product are quantified considering that the vehicles used are internal combustion and operate with diesel as fuel. To calculate transport emissions, it was found that a truck consumes an average of 0.4 L of diesel per kilometer traveled[56] and each liter of diesel produces an average of 2.67 kg of carbon dioxide,[57] therefore

$$CET_{j,m} = DJM_{j,m} \times 0.0065 \qquad \forall\ j, m \tag{11}$$

Calculation of Total Annual Cost and Eco-Indicator 99. The optimal designs and CO_2 capture costs previously obtained for carbon dioxide capture plants operating with amines and eutectic liquids[34,35,58] were taken as the basis for the calculation of the total annual cost and eco-indicator 99. The TAC is used to evaluate economic performance by estimating the investment involved in the process in terms of equipment and auxiliary services. On the other hand, eco-indicator 99 allows the environmental impact generated by the process to be estimated, considering categories such as the steel used in the construction of the equipment and the electricity and steam used as auxiliary services. These metrics have been widely used as economic and environmental targets in the design of processes and supply chains.[59,60] Considering economy of scale, the designs for the capture plants considered were scaled with the carbon dioxide emissions associated with thermoelectric power plants (Table 3). Both capture plants were scaled considering the following emissions: 1.40×10^7 ton/year, 7.00×10^6 ton/year, 4.02×10^6 ton/year, 1.49×10^6 ton/year, 6.93×10^5 ton/year, and their respective costs and environmental impact were calculated using the Guthrie method annualizing it with a 10 year payback time and the EI99 with the respective categories reported in the literature.[61,62] The objective of the scaling is to generate a continuous function to calculate the total annual cost for the different emissions generated by the thermoelectric plants considered in the supply chain. Apparently, the annualized total annual cost has a nonlinear behavior, so it is necessary to simplify the resulting nonlinear function. Using a piecewise linear approximation, it is possible to simplify the nonlinear function into a pseudocontinuous function, basically, the described technique allows to approximate a nonlinear function by making use of several linear traces and the equations that represent them. However, the systems analyzed with their respective emissions showed a behavior close to linear, so in terms of this work a linear behavior was assumed. The slope and the ordinate to the origin obtained for both capture technologies and both metrics are reported in the following table.

Table 3. Slopes and Ordinates at the Origin of the TAC and EI99 Functions

	TAC		EI99	
Technology	m	b	m	b
Amines	202.93	-2.00×10^6	82.936	-1.00×10^6
DES	168.68	1.00×10^7	66.115	3.00×10^6

Thus, the total annual cost and the eco-indicator 99 will be calculated with eqs 12 and 13, considering the carbon dioxide captured

$$TAC_{i,j} = CC_{i,j} \times m_{TAC} + b_{TAC} \times t_{i,j} \qquad \forall\ i, j \tag{12}$$

$$ECOP_{i,j} = CC_{i,j} \times m_{EI99} + b_{EI99} \times t_{i,j} \qquad \forall\ i, j \tag{13}$$

Finally, to calculate the environmental impact and the total annual cost associated with all the capture plants installed, they are calculated as follows

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$$\mathrm{TTAC} = \sum_i \sum_j \mathrm{TAC}_{i,j} \tag{14}$$

$$\mathrm{TECO} = \sum_i \sum_j \mathrm{ECOP}_{i,j} \tag{15}$$

In addition, the P_i coefficients corresponding to each technology were obtained, which indicate how many tons of carbon dioxide are emitted for each ton of carbon dioxide captured. The coefficient for the technologies corresponds to 0.9799 for amines and 0.7283 for deep eutectic liquids.

Objective Function. The optimization model is formulated as a multiobjective problem, considering economic, environmental and social objectives and solved using "ε-constrain" method. The objective function, presented in eq 16, includes the maximization of the annual Profit, the minimization of the environmental impact by minimizing the EI99, and the maximization of the job generation in the various activities involved in the supply chain.

$$\max(\mathrm{Profit}, \mathrm{Jobs}, -\mathrm{EI99}) \tag{16}$$

In addition, two additional metrics were included, the net balance of emissions and social welfare, which are environmental and social metrics, respectively.

Economic Objective. The economic objective seeks to maximize the annual Profit (USD/year), this objective function is given by the difference between annual sales and the sum of transportation costs and the annual cost associated with the installed capture plants. In this sense, the function for the calculation of this economic objective can be expressed mathematically as follows

$$\mathrm{Profit} = \mathrm{TPS} - \mathrm{TTAC} - \mathrm{VTC} - \mathrm{FTC} \tag{17}$$

where TPS represents total product sales, this value is obtained using an average price for carbon dioxide and total product shipped to markets. The average price of carbon dioxide in tons for high-purity markets (99%) is \$423/ton, and for low-purity markets (95%) it is \$362/ton.[63] The complete mathematical function for the calculation of Profit is shown below

$$\begin{aligned} \mathrm{maxProfit} = & \sum_j \sum_{MA} S_{j,MA} \times 423 + \sum_j \sum_{MI} S_{j,MI} \times 362 \\ & - \sum_i \sum_j TAC_{i,j} - 0.0069 \sum_j \sum_m DJM_{j,m} \\ & - 3.126 \sum_j \sum_m S_{j,m} \end{aligned} \tag{18}$$

Environmental Objective. The environmental impact of the supply chain was quantified through an analysis of the EI99, a methodology based on the life cycle assessment developed by Goedkoop.[64] The EI99 has proven to be an effective tool for assessing environmental impact in supply chains and has been successfully used in numerous previous studies.[65−67] This objective consists of two terms, where the first one is associated with the environmental impact generated by the installed carbon dioxide capture plants, while the other term corresponds to the environmental impact generated by the transportation of the product to the markets.

$$\min \mathrm{EI99} = \sum_i \sum_j ECOP_{i,j} + ETJM \sum_j \sum_m S_{j,m} \tag{19}$$

where $ETJM$ corresponds to the parameter associated with the environmental impact generated by the transportation of the products, this parameter is given in pts/ton.

Social Objective. The implementation of social objectives allows a comprehensive evaluation of the performance of a supply chain by estimating its impact on society. As previously mentioned, the social objective considered is the generation of jobs; this objective is calculated using the Jobs and Economic Development Impact (JEDI) method developed by NREL.[68] This methodology estimates the generation of jobs through the economic impact that would represent the inclusion of some project in a given region. The methodology considers three types of jobs, direct, indirect and induced. Direct jobs are those generated during the construction and development of the project. Indirect jobs are related to jobs outside the project site; this type of work includes jobs for transportation, manufacturing, distributors, etc. Finally, induced jobs are those generated by the economic impact of the project.

The multipliers needed for this methodology were estimated using information from different governmental organizations in Mexico, the IMPLAN model and NREL.[55,68,69] The equations describing the JEDI methodology are shown below

$$\begin{aligned} \mathrm{maxJobs} = & \sum_i \sum_j JCP_j^{Direct} \cdot PCC_{i,j} \\ & + \sum_i \sum_j JCP_j^{\mathrm{Indirect}} \cdot PCC_{i,j} \\ & \sum_i \sum_j JCP_j^{\mathrm{Induced}} \cdot PCC_{i,j} \\ & + \sum_i \sum_j JOP_j^{Direct} \cdot UC_{i,j} \\ & + \sum_i \sum_j JOP_j^{Indirect} \cdot UC_{i,j} \sum_i \sum_j JOP_j^{Induced} \cdot UC_{i,j} \\ & + 0.0069 \sum_j \sum_m JT^{Direct} \cdot y_{j,m} \cdot djm_{j,m} \\ & + 3.126 \sum_j \sum_m JT^{Direct} \cdot S_{j,m} + 0.0069 \\ & \sum_j \sum_m JT^{Indirect} \cdot y_{j,m} \cdot djm_{j,m} + 3.126 \\ & \sum_j \sum_m JT^{Indirect} \cdot S_{j,m} + 0.0069 \\ & \sum_j \sum_m JT^{Induced} \cdot y_{j,m} \cdot djm_{j,m} + 3.126 \\ & \sum_j \sum_m JT^{Induced} \cdot S_{j,m} \end{aligned} \tag{20}$$

Additional Metrics. One of the additional metrics included to evaluate the performance of the supply chain was the net balance of emissions, this net balance was carried out considering the carbon dioxide captured, not captured, emitted by the installed capture plants, and emitted by the transportation of the product to the markets. However, it is important to note that the carbon dioxide emissions in the disposal of each specific market are not quantified. Thus, the equation that describes our balance of emissions is as follows

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$$\mathrm{BNE} = \sum_i \sum_j \mathrm{CE}_{i,j} + \sum_j \sum_m \mathrm{CET}_{j,m} - \sum_i \sum_j \mathrm{CC}_{i,j} \quad (21)$$

Thus, if our net balance is negative, we capture more carbon dioxide than we emit, and if it is positive, we emit more carbon dioxide than we capture.

The other additional metric used to evaluate the supply chain is social welfare, which indicates the degree of market satisfaction depending on the percentage of satisfied demand. This metric was proposed as follows for each market

$$\mathrm{SW}_m = \frac{1}{\mathrm{DM}_m}(\mathrm{DM}_m - \sum_j S_{j,m}) \qquad \forall\ m \quad (22)$$

Thus, the SW of each market will be 0 if its demand is completely satisfied and 1 if the demand was not satisfied. Finally, summing up the individual SWs we obtain the following metric

$$\mathrm{TSW} = \sum_m \mathrm{SW}_m \quad (23)$$

This new metric encompasses all markets and will range from 0 to 42, where 0 indicates that all markets were satisfied and 42 indicates that no markets were satisfied. This metric should be as close to 0 as possible.

■ RESULTS AND DISCUSSION

This section presents the analysis of the results obtained for the supply chain optimization model, which was formulated as a mixed-integer linear programming (MILP) problem. The problem was solved using the GAMS software with the CPLEX solver. The size of the model is notable, comprising 5,305 equations, 5,200 binary variables, and 1,232 discrete variables, which reflects the detailed nature of the problem being modeled, particularly in representing the different supply chain stages, markets, and technological processes. The computational resources used for solving the model included a computer equipped with a 12th Gen Intel(R) Core (TM) i5−1240P @ 3.30 GHz processor and 16 GB of RAM operating at 4800 MHz. The computation time for each point on the Pareto diagrams was remarkably fast, with a processing time of only 0.1 s per point, which indicates the efficiency of the CPLEX solver for handling large-scale MILP models of this nature.

Figures 3−5 visually represent the results through Pareto fronts, which are essential for understanding the trade-offs between different objective functions in the optimization process. On the three Pareto fronts, we have points of different colors, each color representing the use of a particular technology or the use of both. The key objective for emissions is to minimize them as much as possible, targeting a net balance that is as negative as feasible, reflecting the system's potential to reduce greenhouse gases. On the other hand, social welfare is measured across 42 markets, with the best-case scenario being a social welfare index of 0, indicating that all markets are fully satisfied, i.e., the demands of all markets are met without shortfall or surplus. The markets involved are distributed as follows: M1−M2 correspond to urea, M3−M5 to petroleum, M6−M9 to methanol, M10−M15 to the Fischer−Tropsch process, and M17−M18 to the soft drinks sector. This breakdown reflects the diverse nature of the supply chain, spanning various key industrial sectors.

In Figure 3, the Pareto front representing the trade-off between Profit and the EI99 environmental impact metric is

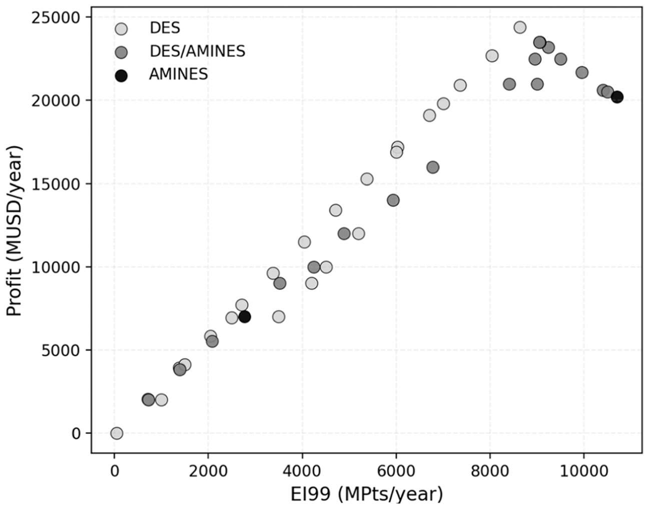

Figure 3. Profit-EI99 Pareto front.

displayed. The EI99 metric is a comprehensive measure of environmental impact, encompassing various categories such as human health, ecosystem quality, and resource depletion. The observed behavior of this Pareto front is a direct result of the constraints embedded within the model, as well as the associated investment and environmental costs linked to the carbon capture technologies considered. The analysis shows a clear differentiation between two distinct technological options: amine-based carbon capture and capture using deep eutectic solvents. The results indicate that the technology utilizing amines as the solvent is significantly more expensive and has a higher environmental impact compared to deep eutectic solvents. The maximum profit, calculated at $ 24,378 million USD per year, is achieved when all thermoelectric plants are equipped exclusively with capture systems that use deep eutectic solvents. In contrast, if amine technology is implemented in all thermoelectric plants, the profit decreases by 17%, and the environmental impact increases by 23%, which underscores the trade-offs between economic and environmental performance when selecting carbon capture technologies.

Moving on to Figure 4, which represents the Pareto front for Profit versus Job Creation, a similar pattern is observed. This correlation is expected since job creation is heavily influenced by the level of capital investment. The more capital-intensive the project, the more jobs it tends to generate, particularly in sectors involving large-scale installations such as carbon capture plants. Therefore, the installation of more capture plants, especially those utilizing the more capital-intensive amine-based technology, results in a higher number of jobs being created. However, this job creation comes at the expense of profitability, as seen in the reduction of profit when amine technology is implemented. The maximum number of jobs generated, 60,944, corresponds to the scenario in which amine-based technology is fully adopted. However, while job creation is maximized, profitability is compromised due to the higher operational and capital costs associated with this technology.

Figure 5 illustrates the Pareto front for Job Creation versus the EI99 environmental impact. This plot reveals a different trend compared to Figures 3 and 4, highlighting the complex

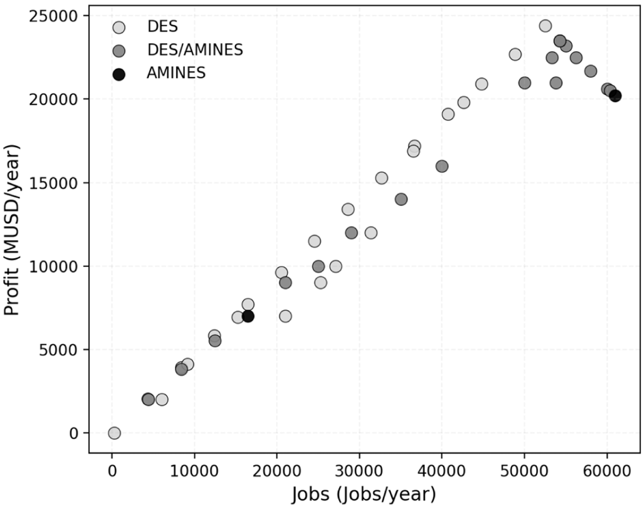

Figure 4. Profit-Jobs Pareto front.

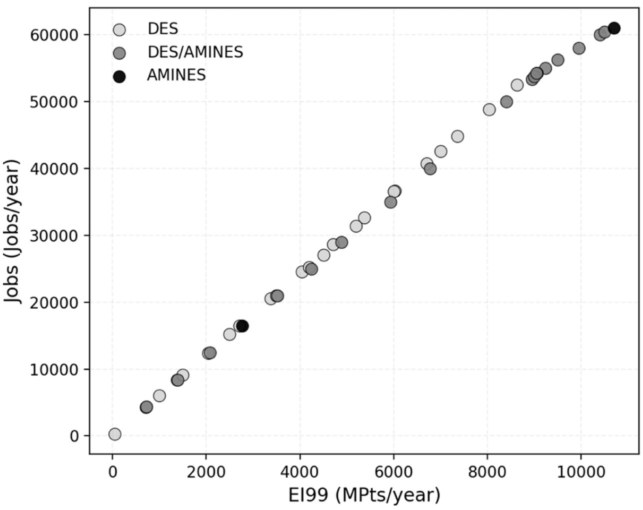

Figure 5. Jobs-EI99 Pareto front.

relationship between environmental impact and employment generation. Interestingly, the maximum number of jobs, again 60,944, coincides with the highest environmental impact, which reaches 10,652 Mpts/year. This result suggests a significant trade-off between environmental sustainability and job creation. Amine technology, while generating more employment due to its capital-intensive nature, leads to a considerable increase in environmental damage, as measured by the EI99 metric. This outcome emphasizes the challenge of balancing economic and social objectives with environmental considerations in the design of industrial systems.

The results from this multiobjective optimization highlight several key insights for decision-making in supply chain management and process design, particularly in the context of carbon capture technologies. First, there is a clear trade-off between economic profitability and environmental impact, as well as between job creation and sustainability. Policymakers and industry leaders need to carefully weigh these factors when choosing between different technologies. While deep eutectic solvents offer a more environmentally friendly and cost-effective solution, they do not generate as many jobs as amine-based technologies. Conversely, while amine technology maximizes employment, it does so at higher environmental and economic cost. These findings underscore the importance of adopting a holistic approach when evaluating carbon capture and other environmental technologies, taking into account not only profitability but also broader societal impacts such as job creation and environmental sustainability.

A more detailed analysis of the solutions presented in the Pareto fronts (Figures 3–5) reveals several key insights into the performance and trade-offs between different carbon capture technologies and their impact on overall supply chain objectives. The total social welfare (TSW) metric reaches its optimal value of 10.57 when the supply chain focuses on soft drink application markets. These markets are characterized by their large number and relatively low demand, allowing for a higher level of satisfaction with stricter purity requirements. By making use of both technologies, supply chain solutions begin to balance the satisfaction of high- and low-demand markets because amine technology is capable of supplying markets with high purity restrictions.

At the point of maximum Profit, the analysis reveals that the solution yields the highest negative emissions (−34.8 $Mton_e$), alongside a TSW value of 37.63. Although this may suggest that the solution is highly effective in terms of reducing carbon emissions, it comes at the cost of satisfying fewer than five markets. Figures 6 and 7 show the response surfaces for the

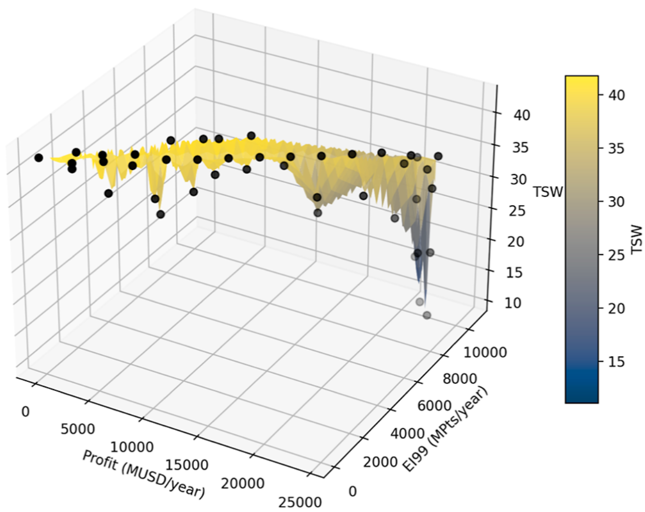

Figure 6. TSW response surface with respect to EI99 and Profit.

additional metrics of net emissions balance (BNE) and total social welfare (TSW), demonstrating the high nonlinearity of these metrics with respect to the Profit, EI99, and Jobs objective functions.

The underlying rationale for this outcome lies in the fact that the optimization model prioritizes larger, industrial markets with minimal purity restrictions, as they offer the highest economic returns. These industrial markets, which are not as concerned with the purity of the captured CO_2, tend to be more economically attractive, leading to a higher Profit margin but a lower TSW. This outcome reflects the inherent trade-offs in the supply chain optimization process, where the desire to maximize Profit may conflict with broader objectives such as market coverage and social welfare. Notably, the deep eutectic solvent (DES) technology is a key factor in this solution, as it generates lower CO_2 emissions per ton captured and is also the most cost-effective option compared to other technologies evaluated in the study. This reinforces the economic viability of

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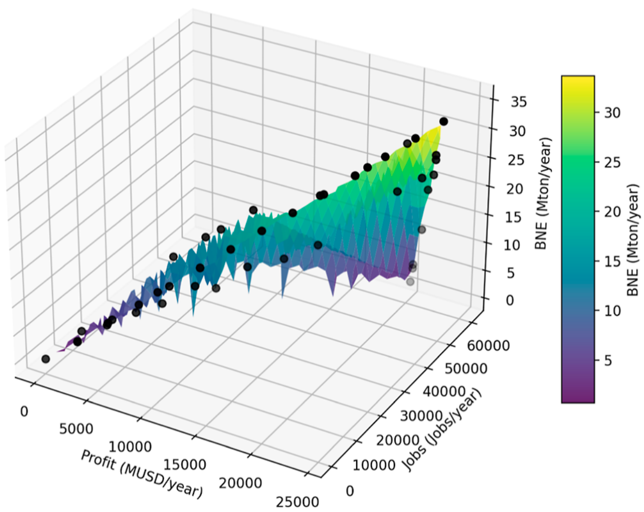

Figure 7. BNE response surface with respect to Jobs and Profit.

DES in scenarios where Profit maximization is the primary objective, but it also highlights its limitations in addressing more stringent market demands.

Finally, a sensitivity analysis was performed to observe the variability of the objective functions when the price of carbon dioxide increases and decreases by approximately 10%, these being \$472.85/ton (MA) and \$404.85/ton (MI) for the case in which the price increases and \$383.47/ton (MA) and \$328.33/ton (MI) when the price decreases. Figures 8–10 show the

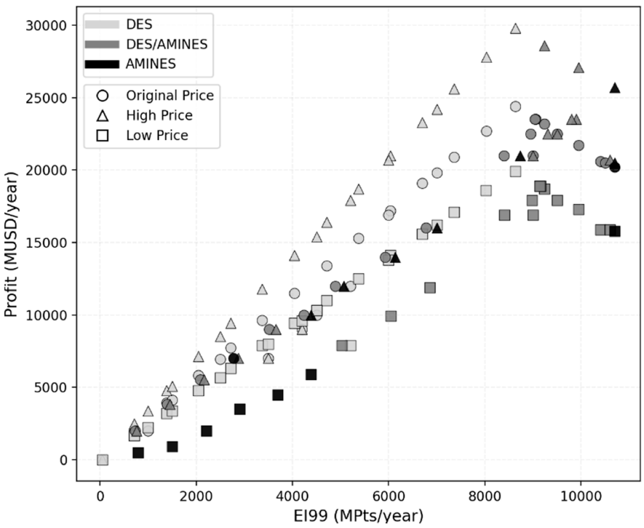

Figure 8. Profit-EI99 Pareto front.

Pareto fronts obtained with the three different prices for carbon dioxide. The results obtained from this variation show results that are expected in the case of the Profit-EI99 and Profit-Jobs pareto diagrams, since the points obtained for low and high prices only show their impact on the net profit performance of the model. However, the environmental impact and job creation follow the same trend regardless of the sale price of CO_2. On the other hand, as environmental and social objectives are not affected, the Jobs-EI99 Pareto maintains a clear trend for all prices, thus demonstrating the relationship between these two metrics.

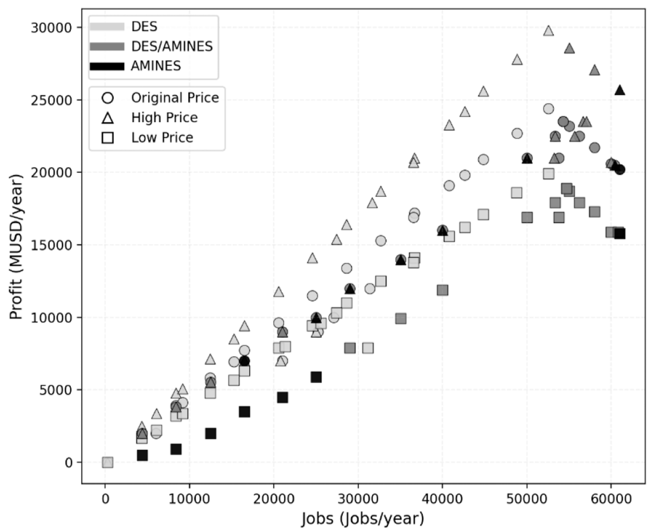

Figure 9. Profit-Jobs Pareto front.

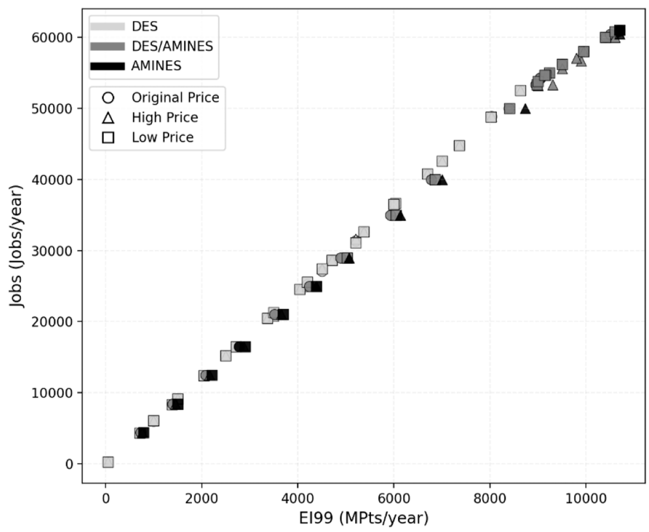

Figure 10. Jobs-EI99 Pareto front.

To identify the most balanced solution in the case of original prices, we implemented a weighting function in three different scenarios, normalizing each metric between 0 and 1 with the maximum and minimum values for each metric. The first scenario considers equal weighting for the metrics (Profit, EI99, Jobs, BNE, TSW), the second scenario considers only the three main metrics (Profit, EI99, Jobs) with an equal distribution, and the last scenario considers the three pillars of sustainability—economic (Profit), environmental (EI99 and BNE), and social (Jobs and TSW)—equally. Figures 11–13 show the top five solutions in these three scenarios in a radar chart. Table 4 shows the results for the solutions shown in Figures 11–13.

The most balanced solution identified through this analysis (Solution 14) strikes a balance between economic, environmental, and social objectives. Specifically, this solution achieves a net profit of \$23,200 million per year, while generating an environmental impact of 9,240 million points per year, creating approximately 55,000 jobs per year, avoiding the emission of 24.2 million tons of CO_2 per year, and achieving a total social welfare (TSW) of 10.63. The fact that the net emissions balance remains negative indicates that more CO_2 is captured

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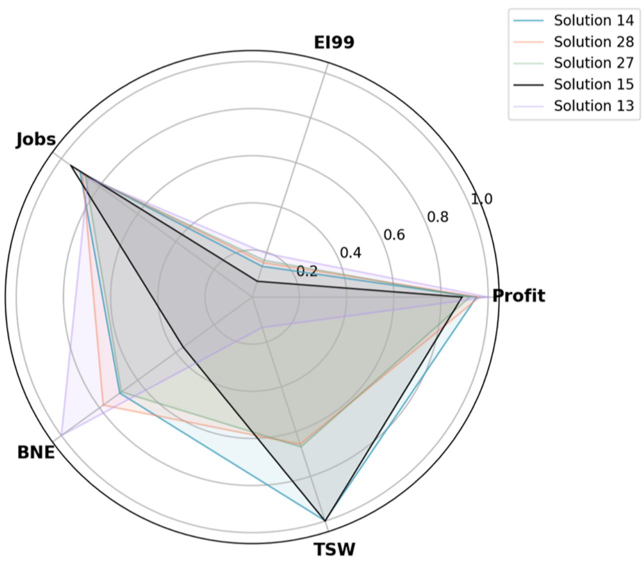

Figure 11. Scenario 1 (equal weight for each metric).

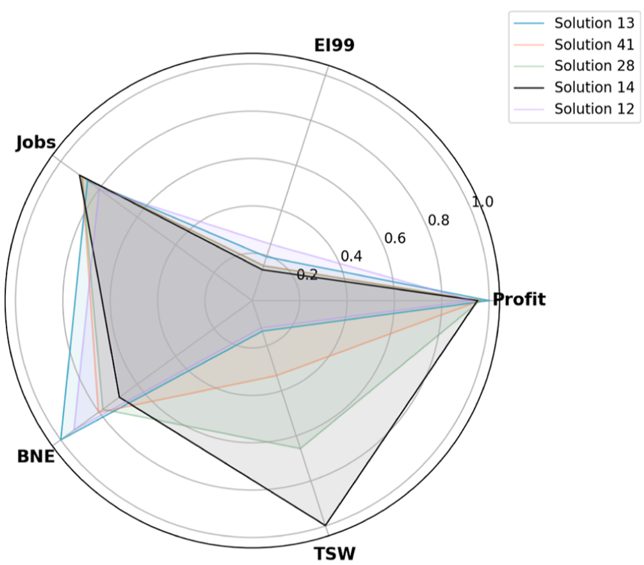

Figure 12. Scenario 2 (equal weight for Profit, EI99 and Jobs).

than is emitted into the atmosphere. This not only demonstrates the effectiveness of combined technologies in achieving carbon neutrality, but also suggests the potential for achieving negative emissions in certain supply chain configurations. Furthermore, a total social welfare (TSW) of 10.63 indicates that this solution satisfies 75% of markets, thus achieving a balance between economic benefits and broad market coverage.

The normalization process using captured CO_2 yielded the following results: \$179.35 per ton of CO_2 captured, 71.57 pts per-ton of CO_2 captured, and −0.19 tons of CO_2 emitted per-ton of CO_2 captured. These normalized values provide a more intuitive understanding of the economic and environmental performance of the supply chain per-ton of CO_2 captured, offering stakeholders a simple way to compare different carbon capture technologies based on their impact on profitability, environmental sustainability, and emissions reduction.

The success of this balanced solution is largely due to the combined use of both carbon capture technologies—DES and amine-based systems—across the supply chain. This approach

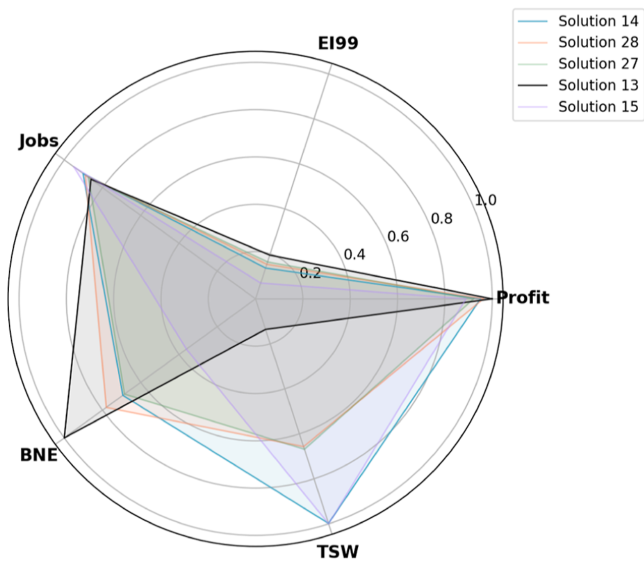

Figure 13. Scenario 3 (equal weight for each pillar).

optimizes performance across both small and large markets, allowing for a more comprehensive and flexible solution that addresses the varying demands of different market segments. The use of amine-based technology presents both opportunities and challenges within this framework. On the positive side, the implementation of amine-based systems leads to a significant increase in job creation, as well as a reduction in TSW. The increase in employment is directly linked to the higher capital investment required by amine technology, which, as observed in many industrial sectors, creates additional job opportunities through the development, installation, and operation of these systems. Furthermore, the reduction in TSW can be explained by the fact that smaller markets, particularly those serving food and pharmaceutical-grade products, have strict purity requirements that can only be met using amine-based technology. This enables the supply chain to capture a larger share of these high-purity markets, thereby improving social welfare metrics. On the other hand, the use of amine-based systems has several negative impacts. These include a higher overall environmental impact, a reduction in Profit, and a decrease in the net emissions balance. The higher environmental impact is due to the fact that amine-based systems are both more costly and more polluting than DES technology. The increased operating costs and greater pollution associated with amine technology result in a lower profitability margin. Additionally, amine technology generates more CO_2 emissions per ton of CO_2 captured, further contributing to the degradation of the net emissions balance. These trade-offs highlight the complex interplay between technology choice, economic viability, and environmental sustainability in the optimization of the supply chain.

Figures 14 and 15 show the supply chain solution described above. In this solution, a total of 28 capture plants are installed: 16 amine plants and 12 deep eutectic liquid plants, which are capable of capturing 99% of the total emissions. As previously mentioned, this solution also satisfies some small markets, such as the soft drink and urea markets. Table 5 shows the amount of CO_2 captured and the technology installed in each thermoelectric plant considered.

A more detailed analysis of Figure 16 reveals crucial information about the percentage of market satisfaction

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Table 4. Best Supply Chain Model Solutions

Solution	Profit (MUSD/year)	EI99 (MPts/year)	Jobs (Jobs/year)	BNE ($Mton_e$/year)	TSW	Sc.1 (score)	Sc.2 (score)	Sc.3 (score)
14	23,200.0	9,240.0	55,015	−24.2	10.63	0.736	0.663	0.771
28	23,500.0	9,060.0	54,272	−27.2	21.31	0.688	0.668	0.734
27	22,500.0	8,950.0	53,333	−23.9	20.94	0.662	0.653	0.705
15	21,700.0	9,950.0	57,998	−12.7	10.57	0.654	0.636	0.693
13	24,400.0	8,630.0	52,252	−34.8	37.63	0.638	0.684	0.698
41	23,500.0	9,040.0	54,275	−28.0	31.46	0.628	0.669	0.684
12	22,700.0	8,030.0	48,835	−32.4	38.07	0.606	0.660	0.660

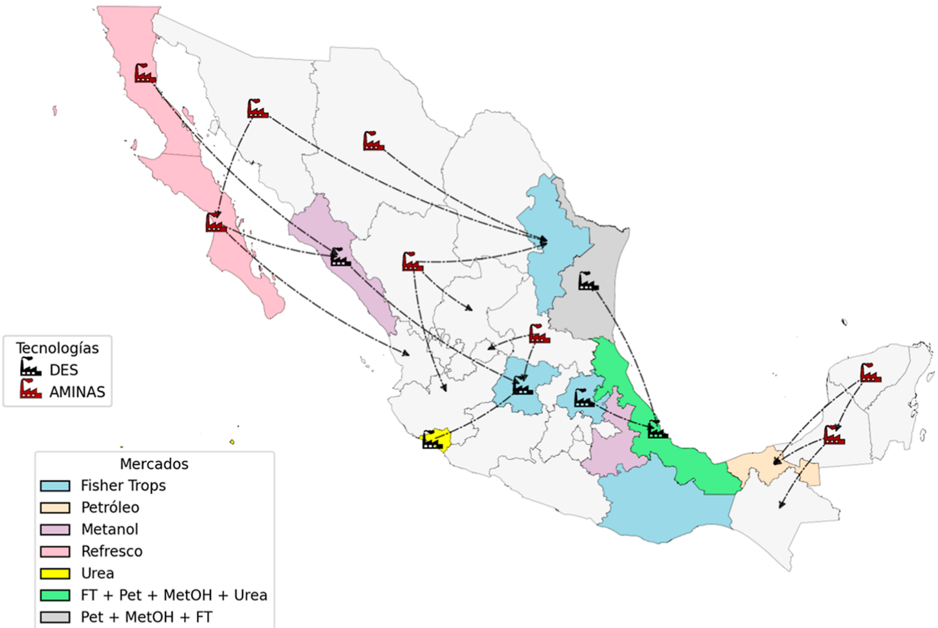

Figure 14. Optimal supply chain solution (conventional thermoelectric power plants).

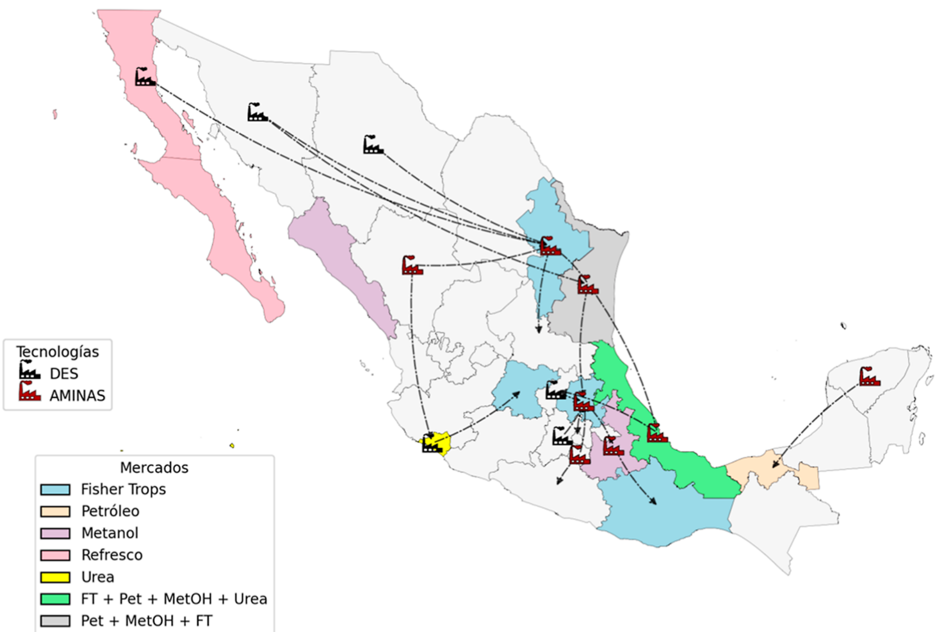

Figure 15. Optimal supply chain solution (combined cycle thermoelectric power plants).

achieved with the optimal solution in different applications. The figure indicates that the percentage of satisfaction varies significantly depending on the application: CO_2 demand in the soft drink market (M16−M42) is fully covered, in the methanol market (M6−M9) it is 94% covered, with market 7 showing the highest percentage of coverage (93%), in the Fischer−Tropsch market (M10−M15) 37% of demand is covered, with market 13 showing the highest percentage of

Table 5. Carbon Dioxide Captured in Thermoelectric Power Plants by Technology

Thermoelectric power plants	Amines (Mton/year)	DES (Mton/year)	Thermoelectric power plants	Amines (Mton/year)	DES (Mton/year)
1	-	4.549	15	1.959	-
2	-	6.986	16	0.692	-
3	-	8.903	17	0.692	-
4	1.470	-	18	3.772	-
5	-	7.887	19	-	7.960
6	3.637	-	20	1.959	-
7	4.017	-	21	-	3.368
8	5.199	-	22	-	9.798
9	2.331	-	23	4.286	-
10	-	3.619	24	-	5.731
11	-	13.917	25	3.870	-
12	1.292	-	26	-	4.898
13	2.804	-	27	-	10.677
14	1.347	-	28	1.488	-

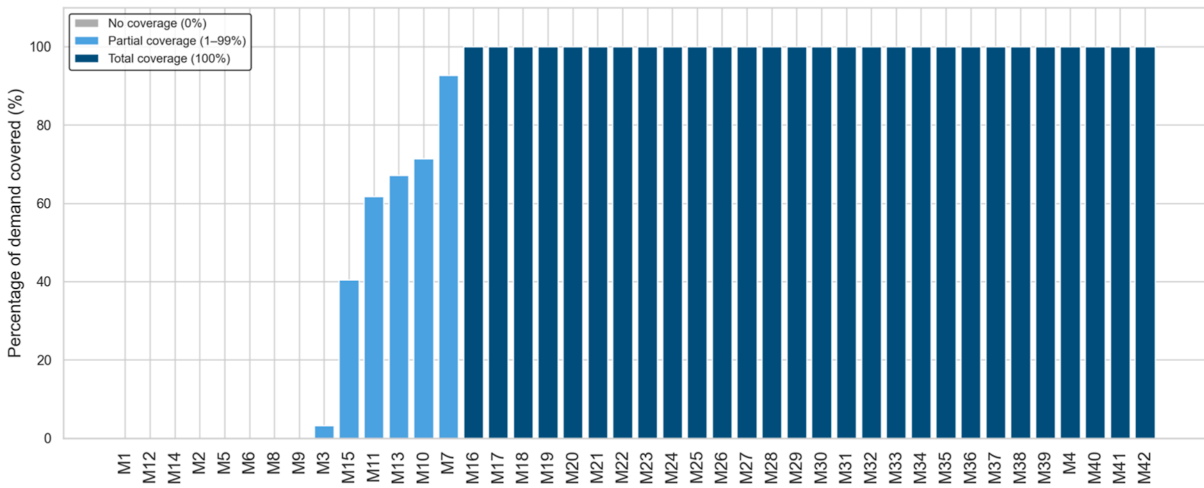

Figure 16. Percentage of demands covered in selected markets.

coverage (67%), in the oil market (M3–M5) 6% of demand is satisfied, fully satisfying the demand of market 4, and finally, in the urea market (M1–M2), no shipments are made and therefore it is not covered by the solution. This disparity underscores the complexity of balancing market demands and the inherent trade-offs that arise when prioritizing certain applications over others.

Petroleum and Fischer–Tropsch process applications present a more challenging scenario. With only 49% of the petroleum market and 21% of the Fischer–Tropsch process market satisfied, it is clear that these applications have more demanding requirements and higher overall demand, which exceeds the available supply of captured CO_2. The failure to meet the total demand for these applications can be attributed to their strict operating criteria, particularly in terms of the volume of CO_2 required. As the optimization model seeks to balance various objectives, such as profit maximization, emissions reduction, and job creation, it becomes necessary to sacrifice some of the satisfaction of these highly demanding markets in favor of easier-to-meet demands in other areas. This trade-off reflects the model's attempt to achieve an optimal balance across the supply chain, where prioritizing less demanding markets can help maximize overall profitability while maintaining a reasonable level of emissions reduction.

These results illustrate the inherent limitations of the supply chain in fully satisfying the needs of all market segments, especially when faced with competing demands from markets with greater economic and environmental implications. In summary, the optimal solution reflects a strategic balance between satisfying market demands, minimizing emissions, and maximizing profitability. The fact that the soft drink market is fully satisfied, while the petroleum, Fischer–Tropsch, and methanol markets are only partially satisfied, demonstrates the complex trade-offs involved in supply chain optimization. The need to sacrifice satisfaction in certain markets, especially the most demanding ones, reflects the limited resources available for CO_2 capture and the competing priorities that must be managed in the optimization process. This analysis highlights the importance of carefully considering market characteristics and the specific limitations of each technology when designing carbon capture and utilization strategies, as different applications will inevitably have different levels of satisfaction depending on their unique requirements and the overall objectives of the supply chain.

Carbon dioxide capture and valorization have become essential strategies in addressing the global challenge of reducing CO_2 emissions. The development and implementation of an integrated supply chain that combines efficient CO_2 capture technologies with valorization pathways are crucial for advancing toward a circular economy and fostering a more sustainable society. One of the most significant barriers to large-scale CO_2 revalorization is the current lack of industrial

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technologies capable of utilizing CO_2 as a feedstock in diverse processes. In this study, we present a supply chain model for capturing CO_2 emissions generated by electricity production in Mexico, focusing on emissions from both conventional and combined cycle thermoelectric plants. Additionally, the model incorporates various CO_2 revalorization technologies, such as the production of methanol, urea, and fuels, with the aim of maximizing economic, environmental, and social benefits. The evaluation of the proposed supply chain model is based on a set of sustainability indicators, which include economic profit, job creation, and environmental impact, to ensure a balanced approach that addresses all three dimensions of sustainability The optimal solution identified by the model demonstrates a high potential for sustainability, with the capacity to capture 129.1 million tons of CO_2 annually. This solution also generates approximately 55,000 jobs and provides a profit of USD 179.35 per ton of CO_2 captured, while achieving an environmental impact score of 71.57 points per ton captured. A key highlight of this solution is its ability to result in a net negative emissions balance of −0.19 tons of CO_2 per ton captured, indicating that more CO_2 is removed from the atmosphere than emitted during the process. The targeted markets for CO_2 revalorization in this model include carbonated beverages, methanol, urea, fuels, and enhanced oil recovery, with fuel production and enhanced oil recovery identified as the most demanding markets. As a result, the supply chain prioritizes these high- and low-demand markets, leaving intermediate-demand markets unaccounted for, resulting in a total social welfare (TSW) score of 10.63, which corresponds to a market satisfaction rate of approximately 75%. The results of this study directly support several of the United Nations Sustainable Development Goals (SDGs) outlined in the 2030 Agenda. Specifically, CO_2 capture from electricity generation contributes to SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) by mitigating greenhouse gas emissions and promoting cleaner energy practices. The adoption of innovative CO_2 capture technologies further promotes SDG 9 (Industry, Innovation, and Infrastructure) by driving technological development and supporting industrial transformation toward more sustainable practices. In conclusion, the proposed supply chain model represents a sustainable approach to CO_2 capture and recovery; however, the analysis also reveals limitations in terms of market equity. While the model achieves significant environmental and economic benefits, it does not consider the urea market, which has intermediate demand. This suggests that, while the model represents a step toward a more sustainable CO_2 management strategy, future improvements should focus on increasing market satisfaction, particularly in intermediate demand markets, to create a more equitable and comprehensive solution.

■ CONCLUSIONS

When interpreting the model outcomes, it is essential to consider the maturity levels of the capture technologies analyzed. Amine-based systems have reached a Technology Readiness Level (TRL) of 8−9, reflecting decades of industrial operation in postcombustion capture plants, particularly in power generation and natural gas processing. Their commercial availability, proven reliability, and established infrastructure make them the only currently deployable option for large-scale CO_2 capture.[70]

By contrast, deep eutectic solvent technologies are still in the early stages of development, with a TRL of 4−5. Current studies remain largely experimental, with only preliminary pilot-scale demonstrations.[71] The inclusion of DES in this model is not intended to suggest immediate feasibility for deployment in the Mexican electricity sector, but rather to explore their potential long-term advantages. DES have demonstrated significantly lower environmental impact and favorable cost projections in preliminary studies, which justifies their consideration as emerging alternatives within a strategic optimization framework.

Consequently, the results involving DES should be interpreted as exploratory scenarios that provide insight into how the supply chain might evolve as new technologies reach commercialization. In the short term, amines will remain the dominant technology; however, the progressive scale-up of DES could enable the transition toward more sustainable capture configurations in the future. Including both technologies in the model thus ensures that the analysis captures not only the current industrial reality but also the potential technological trajectory of CO_2 capture, offering a more comprehensive and forward-looking perspective for policymakers and industry leaders.

Although the optimization model identifies a mixed deployment of amine-based and DES-based systems as the most balanced configuration across economic, environmental, and social objectives, it is important to underline that such a result should be interpreted as a strategic guideline for long-term planning rather than an immediate industrial prescription. In practice, the concurrent adoption of both capture technologies faces several operational barriers. First, infrastructure compatibility must be considered, as each technology presents specific design requirements in terms of solvent management, regeneration energy, and integration with thermoelectric power plants. Second, human resource training and safety protocols will be essential to guarantee adequate operation and maintenance of plants using distinct solvents and process conditions. Third, economic and institutional integration is needed, including financing mechanisms, regulatory alignment, and incentive structures that allow the coexistence of different technologies within a unified supply chain.[72]

To address these challenges, a phased implementation strategy can be envisioned. In the short term, amine-based capture—already commercialized—could continue to dominate, while DES systems advance through pilot-scale demonstrations and precommercial applications. This gradual incorporation would reduce technical and financial risks while paving the way for future large-scale deployment. Thus, the mixed deployment scenario identified by the model should be understood as a roadmap toward sustainable and flexible CO_2 management, reflecting the potential trajectory of the supply chain as emerging technologies mature.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.iecr.5c02324.

Methodology for distance estimation in CO_2 supply chain; description of rhumb line approach for geographic mapping; equations for coordinate conversion and distance calculation; data sets of thermoelectric plant and market locations (latitude/longitude) (PDF)

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Notes

The authors declare no competing financial interest.

NOMENCLATURE

Data sets

$i \in I$ capture technologies
$j \in J$ thermo electricplants
$m \in M$ markets

Data subsets

IM∈M industrial markets
FM∈M food markets

Parameters

η_i efficiency of capture technologies i
E_j carbon dioxide emissions from thermoelectric power plants j
P_i carbon dioxide production coefficient of technology i
b^U maximum carbon dioxide captured
b^L minimum carbon dioxide captured
DM_m demands for carbon dioxide by market m
$djm_{j,m}$ distance for shipping arc $j \rightarrow m$
ETJM environmental impact factor by product transport
JCP_j^{direct} coefficient for generation of direct jobs by construction of plant j
$JCP_j^{indirect}$ coefficient for generation of indirect jobs by construction of plant j
$JCP_j^{induced}$ coefficient for generation of induced jobs by construction of plant j
JOP_j^{direct} coefficient for generation of direct jobs by operation of plant j
$JOP_j^{indirect}$ coefficient for generation of indirect jobs by plant operation j
$JOP_j^{induced}$ coefficient for induced job generation by operation of plant j
JT^{direct} coefficient for generation of direct jobs by product transportation
$JT^{indirect}$ coefficient for generation of indirect jobs by transportation of products
$JT^{induced}$ coefficient for induced job generation due to product transportation

Variables

$CC_{i,j}$ carbon dioxide captured by technology i installed in thermoelectric plant j
$CNC_{i,j}$ carbon dioxide not captured by technology i installed in thermoelectric power plant j
$CPT_{i,j}$ carbon dioxide produced by technology i installed at thermoelectric plant j
$CE_{i,j}$ carbon dioxide emitted by technology i installed at thermoelectric plant j
$S_{j,m}$ Shipment from capture plant to market ($j \rightarrow m$)
$DJM_{j,m}$ distance selected for shipment arc $j \rightarrow m$
VTC variable transportation costs
FTC fixed transportation costs
$CET_{j,m}$ carbon dioxide emitted by transportation for the $j \rightarrow m$ shipping arc
$TAC_{i,j}$ total annual cost for technology i installed at thermoelectric plant j
$ECOP_{i,j}$ EI99 for technology i installed in thermoelectric plant j
$TTAC_{i,j}$ total annual cost of all technologies i installed in thermoelectric plants j
$TECO_{i,j}$ EI99 of all the technologies i installed in thermoelectric plants j
TPS total product sales
$PCC_{i,j}$ capital costs of technology i installed in thermoelectric plants j
$UC_{i,j}$ utility cost of technology i installed in thermoelectric plant j
BNE balance net of carbon dioxide emissions
SW_m social Welfare of each market m
TSW total social Welfare

Binary variables

$t_{i,j}$ binary variable, 1 if technology i is installed in thermoelectric plant j
$y_{j,m}$ binary variable, 1 if the sending arc $j \rightarrow m$ (plant−market) is selected

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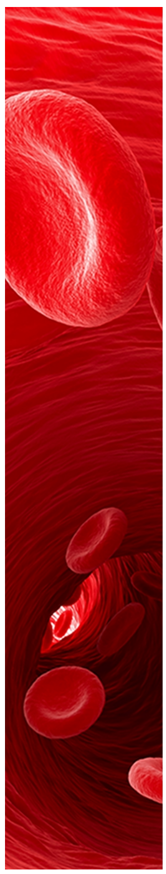

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