Effective Use of Carbon Pricing on Climate Change Mitigation Projects: Analysis of the Biogas Supply Chain to Substitute Liquefied-Petroleum Gas in Mexico

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Keywords: Optimization, carbon emission trading, carbon tax, biogas, fossil fuel substitution

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There is presently an urgent demand for efficient and/or renewable energy technologies to correct global warming. However, these energy technologies are limited mainly by political and economic constraints of high costs and the lack of subsidy. Carbon-pricing strategies, such as carbon-emission taxes and carbon-emission trading schemes, may reduce this gap between sustainable and unsustainable energy technologies. Therefore, this paper seeks to analyze both of these carbon-pricing instruments in the Mexican energy sector to promote upgrading biogas investment and to substitute liquified petroleum gas consumption using an optimization approach. Furthermore, we propose a multi-objective optimization approach to encourage investment in the biogas supply chain supported by an effective use of carbon-pricing schemes. A case study of the central western region of Mexico was made to analyze the performance of the proposed methodologies. The results show that carbon-emission taxes and carbon-emission trading systems stimulate, with some limitations, the investment in biogas projects for fossil fuel substitution. Nevertheless, using the proposed multi-objective optimization formulation leads the discovery of a more efficient use of the above-mentioned carbon-pricing schemes, thus reaching higher economic and environmental benefits than traditional carbon-pricing policies, with a lower cost/price per ton of carbon dioxide equivalent.

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Abstract: There is presently an urgent demand for efficient and/or renewable energy technologies to correct global warming. However, these energy technologies are limited mainly by political and economic constraints of high costs and the lack of subsidy. Carbon-pricing strategies, such as carbon-emission taxes and carbon-emission trading schemes, may reduce this gap between sustainable and unsustainable energy technologies. Therefore, this paper seeks to analyze both of these carbon-pricing instruments in the Mexican energy sector to promote upgrading biogas investment and to substitute liquified petroleum gas consumption using an optimization approach. Furthermore, we propose a multi-objective optimization approach to encourage investment in the biogas supply chain supported by an effective use of carbon-pricing schemes. A case study of the central western region of Mexico was made to analyze the performance of the proposed methodologies. The results show that carbon-emission taxes and carbon-emission trading systems stimulate, with some limitations, the investment in biogas projects for fossil fuel substitution. Nevertheless, using the proposed multi-objective optimization formulation leads the discovery of a more efficient use of the above-mentioned carbon-pricing schemes, thus reaching higher economic and environmental benefits than traditional carbon-pricing policies, with a lower cost/price per ton of carbon dioxide equivalent.

Keywords: fossil fuel substitution; biogas; carbon tax; carbon emission trading; optimization

1. Introduction

Global demand of resources and energy has grown exponentially to such extent that one sustainable development goal is to “take urgent action to combat climate change and its impacts” [1]. Presently, a huge effort is being made to develop new technologies for efficient energy production and substitute fossil-fuel-based technologies to achieve a reduction in the emissions required to limit global warming to 1.5 °C above pre-industrial temperatures as required by the Paris Agreement. However, those options are limited by political, economic and technical constraints, which increase the level of financial risk to many stakeholders [2]. To support energy efficiency or renewable energy use, rigorous international and domestic energy and environmental policies to reduce greenhouse gas (GHG) emissions are enforced due to GHGs’ potentially damaging effects on the environment [3]. These policies play important roles in ensuring energy supply security, coordinating energy with economic development and environmental protection, as well as addressing global climate change [4]. For example, carbon pricing provides a financial incentive for consumers and producers to invest in technologies that reduce emissions. This not only encourages the adoption of existing low-carbon technologies, but also indirectly promotes the development of new ones [5]. Carbon taxes (CT) and emissions-trading system (ETS) are two globally practiced carbon regulatory policy schemes [6,7]. The CT scheme aims to control emissions by taxing the generated carbon. Each greenhouse gas emitter is charged a tax proportional to the size of the generated emissions [8], so the prices of products and services are increased and the demand for them may reduce. The advantage of implementing a CT system is to encourage the use of alternative sources of energy by making them cost-competitive with cheaper fuels [9]. On the other hand, in the ETS, the right to emit carbon is tradable, and the participants with high abatement costs will spend money on buying emission rights to emit more, while the participants with low abatement costs are being rewarded for their avoided emissions [10]. The main advantage of implementing emissions trading is to ensure that essential reductions in GHG emission targets are met at the lowest possible cost. The other main advantage of this program is to provide the private sector with the flexibility required to reduce emissions while stimulating technological innovation and economic growth. This mechanism provides financial support for greenhouse gas emission reduction projects; nevertheless, the effects in different regions and different sectors would be different under the same pattern [11]. The World Bank reported in 2018 that 51 carbon-pricing initiatives have been implemented or are scheduled for implementation, which consists of 25 ETS and 26 CT. These carbon-pricing initiatives would cover 11 gigatons of carbon dioxide equivalent ($GtCO_2e$) or about 20% of global GHG emissions. The total value of ETS and CT was US$82 billion, representing an increment of 56% compared to the 2017 value of US$52 billion [12]. Carbon pricing has become one of the most important strategic programs used by China to achieve its targets of energy conservation and carbon-emission mitigation [13]. However, some countries use the carbon revenues to supplement government general funds and the revenue is not using in carbon mitigation alternatives [14]. Currently, carbon prices vary substantially, from less than US$1/$tCO_2e$ to a maximum of US$139/$tCO_2e$; however, most jurisdictions have carbon prices that are substantially lower than those needed to be consistent with the Paris Agreement (between US$40 to US$80) [12].

This paper seeks to analyze the effect of the above-mentioned carbon-pricing instruments in the Mexican energy sector, contrasting CT with an ETS to promote the investment in productive activities to substitute liquified petroleum gas (LPG) with upgraded biogas using a new optimization approach. Furthermore, we proposed a multi-objective optimization approach to encourage the investment of an upgraded biogas value chain supported by an effective use of carbon-pricing schemes.

LPG is a gas product of petroleum refinement consisting of propane, some propylene, butane and other light hydrocarbons. This fuel is stored and sold in cylinders (vessels of moderate pressure), in a liquid form [15]. Mexico has an extensive network of pipelines, spanning 1835 km in length, for importing LPG from Texas and transporting it to other parts of the country. In Mexico, this fuel is used in agricultural and industrial sectors, but from the total volume of LPG consumed in Mexico (283.0 thousand barrels per day in 2015), the residential sector had a share of 59.5%. In the residential sector, LPG is mainly used for heating water and cooking. By the end of 2015, the total demand for fuels in the residential sector was of 305.9 thousand barrels per day of LPG equivalent. From this volume, 55% was LPG, the firewood with 37.0%, and finally, natural gas with a 8.0% share (due to the lack of infrastructure) [16]. The substitution of LPG for other energy sources such as electricity and natural gas (NG) in the residential sector is limited due to different situations. First, electricity price is higher than LPG and the investment made in household appliances that use LPG represents a strong factor to migrate to this alternative. Then, the substitution of LPG for natural gas depends on the existence of infrastructure (pipes) to distribute NG to every house, the prices of both fuels, and the readiness or economic capacity of users to connect to the NG network and pay a monthly fee for the service; therefore, because of limited NG network the LPG substitution for NG in Mexico is low and it does not have a promising outlook [17]. On the other hand, biogas is a valuable renewable energy source produced from biodegradable organic materials such as industrial waste, sewage sludge, animal manure, and agricultural resides via anaerobic digestion, which can be used as a source for thermal energy, electrical power or chemicals [18–20]. The main products of anaerobic digestion are methane-rich biogas and nutrient-rich digestion residue (digestate) that can be used as a fertilizer directly or after processing [21]. Moreover, anaerobic digestion may contribute to mitigate odors associated with manure storage and decomposition and removes pathogens that can pose significant risk to human and animal health, and reduces GHG emissions released into the atmosphere by avoiding methane emissions from natural decomposition during storage [22,23]. The major components of biogas are CH_4 and CO_2, but it also contains H_2S and other sulfur compounds, halogenated compounds, siloxanes, water, ammonia, and other volatile organic compounds. The effects of these impurities in biogas are accumulation of water in pipes, SO_2 and SO_3 formation during combustion, reduction of calorific value, and mainly corrosion in equipment [24]. The removal of these contaminants especially H_2S and CO_2, will significantly improve the quality of the biogas for its further uses. Basically, there are two steps involved in biogas treatment; cleaning (removal of harmful and toxic compounds such as H_2S), and upgrading (adjustment of CO_2 content, to increase the calorific value of the biogas to optimal level). The selection of appropriate technology depends on the specific biogas requirements, site-specific, local circumstances, and is case-sensitive. Biomethane is the final product, which is composed of CH_4 (95%–99%) and CO_2 (1%–5%), with little or no trace of H_2S [19]. The steps to obtain the final product represent a challenge in terms of capital and operating costs and energy consumption that represent disadvantages to introduce biogas in a market to compete with other fuel despite the potential environmental benefits; even so, an effective carbon-pricing scheme can increase the cost/price of intense carbon-emitting technologies and activities, and at the same time can provide a financial incentive for consumers and producers to invest in technologies to reduce GHG emissions. This not only encourages the adoption of existing low-carbon technologies, but also indirectly promotes the development of new ones [5]. Some works have studied the effect of carbon pricing to promote low-carbon alternatives in industrial processes [25], supply chains [26], and residential building complexes [27,28]. For example, Gonela [29] showed the environmental and economic advantages and disadvantages of various carbon-emission schemes (carbon cap and trade, carbon cap, and carbon tax) on the design of hybrid electricity supply chains, which mix coal-based and biomass-based electricity generation. Yu et al. [30] studied different emission tax policies in a multitiered supply chain network and their results showed that tax policies combined with other factors can help to reduce the total carbon footprint, supporting more sustainable technologies for transportation. Bing et al. [31] proposed the use of ETS as an instrument for facilitating a global recycling network. The key decision is the relocation of plastic reprocessing plants (i.e., moving from Europe to China), and the results show that ETS encourages to switch to a lower-emission production process, which leads to reduced emission in the reprocessing sector, and relocation possibilities improved the performance of the network, which reduced the total costs and transport emission. This paper is focused on the study of the effect of a large-scale substitution of fossil fuel for renewable fuel in the west sector of Mexico to take advantage of the high production of animal manure, municipal organic waste, sewage sludge and agricultural residues. In this case, ETS and CT are used to support the consumption of renewable energy. Additionally, we combined a multi-objective optimization method with ETS to improve the environmental and economic advantages of this scheme.

2. Problem Statement

The problem addressed in this work covers 40 cities in Mexico located in the west-central region as presented in Figure 1. This region has an intense livestock activity and, therefore, a high potential for biogas production.

This paper seeks to encourage the replacement of fossil fuels with renewable fuels using carbon-pricing schemes and we present three different cases to analyze their effect. In the first case, a CT scheme is assessed regarding the emissions generated by fossil fuels (i.e., the renewable fuel production is stimulated), and it is expected that the GHG emissions can decrease due to a penalization on the GHG emissions generated by fossil fuel. In the second case, an ETS is used to pay an economic incentive on GHG emission-saving generated using renewable energy and then, to stimulate the replacement of fossil fuel. In the third case, a multi-objective optimization formulation is proposed to obtain more efficient use of the above-mentioned carbon-pricing schemes. In this sense, the optimal design of a supply chain for biogas is used to compare these three alternatives. The decision variables involved include the location and size of biogas plants, type of biogas production technology, purification technology, biomass supplier sites, type of biomass to be used and the selection of the markets where the biogas will be sold.

Figure 1. Geographical region for the problem.

Figure 2 shows the location of biomass suppliers and potential localization of upgrading biogas technologies (blue points). This figure also represents an example of the possible connections between the cities, where each city has an amount of available biomass and energy requirements; this biomass can be sent to other cities or can be used locally to produce biogas. Also, in each city a plant for biomass processing and/or a plant for biogas purification and upgrading can be installed. The amount of biomass required by each city and the size and location of purification and upgrading plants change as a function of the energy demand of each city, the available biomass and the transport cost of raw materials and products. For example, if three random cities are chosen (in this example, the cities with red, blue and black lines), these three cities may send biomass and/or biogas to any other city even the raw material and products may be sent or received between them (green lines). However, this interaction between cities and the installation of a new plant is feasible only if they bring economic and environmental benefits.

The optimization model is based on previous contributions [32], and Figure 3 presents the schematic representation of the biogas supply chain in competition with a fossil fuel (fresh fuel). This superstructure is divided into three main sections: biogas supply chain, flowrate of fresh fuel, and energy demand. The biogas supply chain is subdivided into three sections: biomass source, processing, and purification technologies, where the biomass type i can come from any supply source f and it is transported to location l to be processed with a production technology j to produce non-purified biogas and digestate. The digestate can be sold to the market and the non-purified biogas is transported to location m to be upgraded with a purification technology k to produce purified biogas (called biogas in the next sections). The purified biogas can be sold to market p to satisfy the energy demand. As can be seen in Figure 3, the biogas will be in competition with the fresh fuel to satisfy the energy demand considering that the fresh fuel has all the necessary infrastructure to be sold in market p. The model formulation and considerations of biogas supply- chain investment to substitute the fresh fuel are described in the next section.

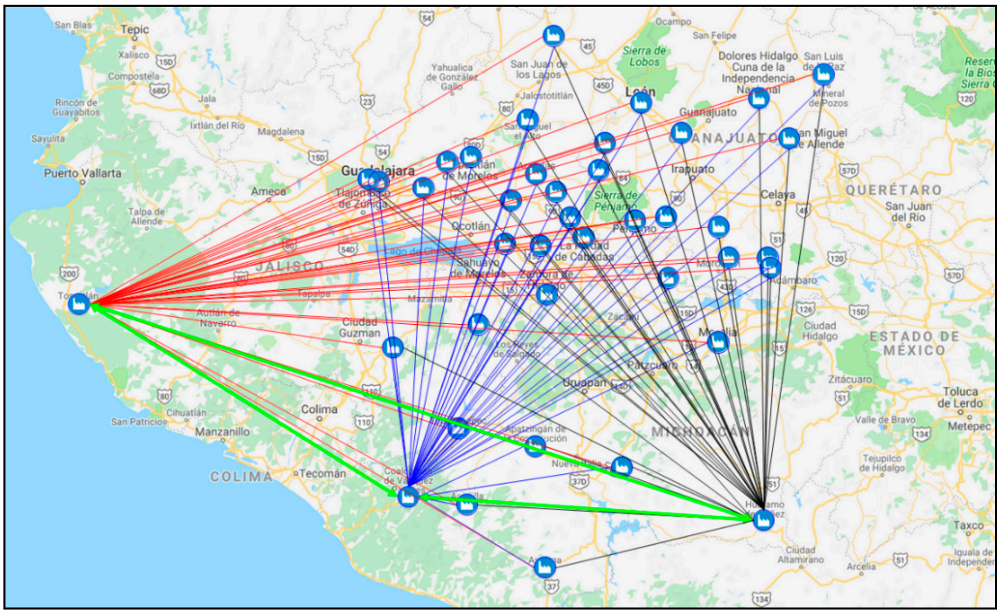

Figure 2. Different locations of biomass suppliers and potential localization of upgrading biogas technologies.

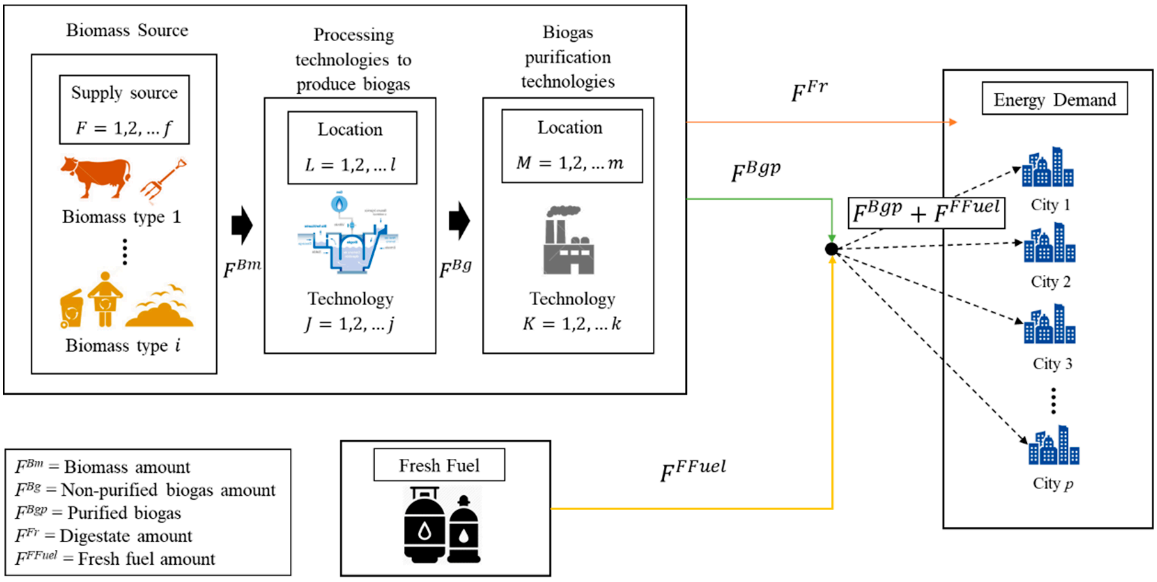

Figure 3. Superstructure for the proposed system.

3. Model Formulation

The mathematical formulation is derived from a previously published optimization approach [32]. The referenced work consists of synthetizing a biogas supply chain to satisfy the demand in a geographical region through the optimal installation of processing and purification technologies using different types of available biomass as well as determining which technology should be installed considering economic and environmental aspects. In this project, the model includes similar mass balances and similar performance equations of the processing and purification technologies. However, it considers the competition with other currently used fuel (LPG, natural gas, shale gas, etc.), named fresh fuel in the model formulation. All this is based on the superstructure shown in Figure 3 and developed as a multi-objective optimization formulation, which includes an economic function and environmental considerations. On environmental considerations, the model only includes the GHG emissions generated by the fresh fuel because the model compares the combustion emissions under next considerations. The GHG emissions by biogas combustion and biomass/digestate may be considered insignificant because they come from biomass and these do not modify the balance of atmospheric CO_2 (carbon cycle); i.e., CO_2 emissions by combustion are considered to be biogenic due to the biogas coming from biomass and in turn the biomass coming from the capture of atmospheric CO_2 [33]. Although in a previous work [32], the upstream emissions (by transportation, use of production and purification technologies) have been considered in the study of the biogas project, in this work, the upstream emissions are not taken into consideration due to several studies showing the upstream emission factors to biogases, natural gas, and petroleum products are 14.9, 12.8, and 10.7 g CO_2eq MJ^{-1} [34], respectively. Also, it has been reported that the average of upstream emissions for different fuels is in a range of 11.3 to 16.8 g CO_2eq MJ^{-1} which represents a small portion in comparison to the value of combustion [35], and the difference between upstream emissions is minimum. Therefore, the proposed mathematical formulation is presented below.

3.1. Mass Balances and Constraints of Supply Chain

The balances and constraints are described starting from upstream to downstream for every section presented in Figure 3.

In the biomass source section: the constraint of biomass availability is described by Equation (1) The sum for each required biomass i in all locations l coming from each supply source f ($F^{Bm}_{i,f,l,t}$) must be lower than or equal to the amount of available biomass in each source ($\vartheta^{Bm}_{i,f,t}$):

$$\sum_{l} F^{Bm}_{i,f,l,t} \leq \vartheta^{Bm}_{i,f,t} \qquad \forall\ (i \in I, f \in F, t \in T) \tag{1}$$

Before processing biomass: Equations (2) and (3) represent the mass balances before the biomass is processed. The amount of total biomass in each processing location l ($F^{Bm\_Total}_{i,l,t}$) must be equal to the sum of biomass amount coming from all sources ($F^{Bm}_{i,f,l,t}$) and also it must be the sum of the biomass amount that can be distributed to all processing technologies j to be converted in biogas ($F^{Bm\_conv}_{i,l,j,t}$).

$$F^{Bm\_Total}_{i,l,t} = \sum_{f} F^{Bm}_{i,f,l,t} \qquad \forall\ (i \in I, l \in L, t \in T) \tag{2}$$

$$F^{Bm\_Total}_{i,l,t} = \sum_{j} F^{Bm\_conv}_{i,l,j,t} \qquad \forall\ (i \in I, l \in L, t \in T) \tag{3}$$

In the processing technologies section: Equations (4) and (5) represent that the amount of total biogas generated by different biomass sources in each processing location ($F^{Bg\_Total}_{i,l,t}$) must be equal to the sum of biogas amount coming from all processing technologies that may be used in each processing location ($F^{Bg}_{i,l,j,t}$) and also it must be equal to sum of the biogas amount which is transported to location m ($F^{Bg}_{i,l,m,t}$). In addition, the total digestate amount in location l from each biomass source ($F^{Fr\_Total}_{i,l,t}$) must be equal to the sum of digestate amount coming from all processing technologies ($F^{Fr}_{i,l,j,t}$) and it must be equal to the sum of digestate distributed to market q ($F^{Fr\_dem}_{i,l,q,t}$) (Equations (6) and (7)). Equation (8) describes the total digestate amount demanded in market q ($F^{Fr\_dem\_Total}_{i,q,t}$).

$$F^{Bg\_Total}_{i,l,t} = \sum_{j} F^{Bg}_{i,l,j,t} \qquad \forall\ (i \in I, l \in L, t \in T) \tag{4}$$

$$F_{i,l,t}^{Bg\_Total} = \sum_{m} F_{i,l,m,t}^{Bg} \qquad \forall\ (i \in I, l \in L, t \in T) \tag{5}$$

$$F_{i,l,t}^{Fr\_Total} = \sum_{j} F_{i,l,j,t}^{Fr} \qquad \forall\ (i \in I, l \in L, t \in T) \tag{6}$$

$$F_{i,l,t}^{Fr\_Total} = \sum_{q} F_{i,l,q,t}^{Fr\_dem} \qquad \forall\ (i \in I, l \in L, t \in T) \tag{7}$$

$$F_{i,q,t}^{Fr\_dem\_Total} = \sum_{l} F_{i,l,q,t}^{Fr\_dem} \qquad \forall\ (i \in I, q \in Q, t \in T) \tag{8}$$

The amounts of biogas and digestate generated by the processing technologies are related to flowrate processed in each technology through an efficiency factor ($\chi_{i,j}^{Bg}$ and $\chi_{i,j}^{Fr}$ respectively) (Equations (9) and (10)).

$$F_{i,l,j,t}^{Bg} = \chi_{i,j}^{Bg} \times F_{i,l,j,t}^{Bm\_conv} \qquad \forall\ (i \in I, l \in L, j \in J, t \in T) \tag{9}$$

$$F_{i,l,j,t}^{Fr} = \chi_{i,j}^{Fr} \times F_{i,l,j,t}^{Bm\_conv} \qquad \forall\ (i \in I,\ l \in L, j \in J, t \in T) \tag{10}$$

The capacities of production technologies are described by Equation (11) to (12). The amounts of biogas and digestate must be lower or equal to the maximum capacity of these technologies (γ_j^{Bg}, γ_j^{Fr}) and at the same time, they must be greater than the minimum capacity multiplied by a decision variable $y_{j,l}$.

$$\gamma_j^{Bg\_min} \times y_{j,l} \le \sum_{i} F_{i,l,j,t}^{Bg} \le \gamma_j^{Bg\_max} \times y_{j,l} \qquad \forall\ (l \in L, j \in J, t \in T) \tag{11}$$

$$\gamma_j^{Fr\_min} \times y_{j,l} \le \sum_{i} F_{i,l,j,t}^{Fr} \le \gamma_j^{Fr\_max} \times y_{j,l} \qquad \forall\ (l \in L, j \in J, t \in T) \tag{12}$$

Before upgrading biogas: The total biogas amount, which is purified in location m ($F_{i,m,t}^{Bg\_conv\_Total}$), must be equal to the sum of biogas generated by all locations l and it must be equal to the sum of biogas distributed to all purification technology k in each location m ($F_{i,m,k,t}^{Bg\_conv}$) (Equations (13) and (14)).

$$F_{i,m,t}^{Bg\_conv\_Total} = \sum_{l} F_{i,l,m,t}^{Bg} \qquad \forall\ (i \in I, m \in M, t \in T) \tag{13}$$

$$F_{i,m,t}^{Bg\_conv\_Total} = \sum_{k} F_{i,m,k,t}^{Bg\_conv} \qquad \forall\ (i \in I, m \in M, t \in T) \tag{14}$$

In the purification technologies section: The total purified-biogas amount (Equations (15) and (16)) generated by each purification technology k in each location m ($F_{k,m,t}^{Bgp\_Total}$) must be equal to the sum of purified biogas amounts coming from all biomass i for each technology k and location m ($F_{i,m,k,t}^{Bgp}$) and it must be equal to the sum of purified biogas distributed to market p ($F_{k,m,p,t}^{Bgp\_dem}$). Equation (17) describes the total biogas amount demanded in market p ($F_{k,m,p,t}^{Bgp\_dem}$).

$$F_{k,m,t}^{Bgp\_Total} = \sum_{i} F_{i,m,k,t}^{Bgp} \qquad \forall\ (k \in K, m \in M, t \in T) \tag{15}$$

$$F_{k,m,t}^{Bgp\_Total} = \sum_{p} F_{k,m,p,t}^{Bgp\_dem} \qquad \forall\ (k \in K, m \in M, t \in T) \tag{16}$$

$$F_{k,p,t}^{Bgp\_dem\_Total} = \sum_{m} F_{k,m,p,t}^{Bgp\_dem} \qquad \forall\ (k \in K, p \in P, t \in T) \tag{17}$$

The yield of purified biogas is given by Equation (17) with its efficiency factor ($\chi_{i,k}^{Bgp}$).

$$F_{i,m,k,t}^{Bgp} = \chi_{i,k}^{Bgp} \times F_{i,m,k,t}^{Bg\_conv} \qquad \forall\ (i \in I,\ m \in M, k \in K, t \in T) \tag{18}$$

The capacities of upgrading technologies are described by Equation (19). The amount of purified-biogas must be lower or equal to the maximum capacity of these technologies (γ_k^{Bgp}) and at the same time, it must be greater than the minimum capacity multiplied by a decision variable $y_{j,l}$.

$$\gamma_k^{Bgp\_min} \times y_{k,m} \le \sum_i F_{i,m,k,t}^{Bgp} \le \gamma_k^{Bgp\_max} \times y_{k,m} \qquad \forall\ (m \in M, k \in K, t \in T) \tag{19}$$

Notice that there is a summation of all biomass type i amounts in each previously cited equation (Equations (11), (12) and (19)). This summation indicates that the product amounts cannot be generated at same time (i.e., each product amount takes a part of time period t). Therefore, the maximum capacity is not indexed for each biomass type i.

Fresh fuel section: the total fresh fuel amount in competition with the biogas is equal to the sum of all cities in market p (Equation (14)).

$$F_t^{FFuel\_Total} = \sum_p F_{p,t}^{FFuel\_dem} \qquad \forall\ (t \in T) \tag{20}$$

Energy demand section: the minimum and maximum energy demands of products are given by Equations (21) and (22). The sum of purified biogas amounts in locations m generated by different technologies plus the fresh fuel amount must satisfy the energy demand of market p. This summation must be lower than or equal to and greater than or equal to the maximum and minimum demand (η^{max} and η^{min}) needed in market, respectively. It should be noticed in Equation (21) that the amounts of biogas and fresh fuel are multiplied by their heating values (H^{Bgp} and H^{FFuel}) and normal density (ρ^{Bg_N}) in order to get consistent units. Since a digestate excess exists, Equation (22) is formulated this way to avoid the biogas production being limited when the maximum demand of digestate is reached. It should be noticed that Equation (21) represents the competition between biogas and fresh fuel (i.e., the energy demand may be satisfied either by biogas and/or fresh fuel).

$$\begin{gathered}\eta_{p,t}^{Fuel\_min} \le \left(\sum_k \sum_m F_{k,m,p,t}^{Bgp\_dem}\right) \times H^{Bgp} \times \rho^{Bg\_N} + \left(F_{p,t}^{FFuel\_dem} \times H^{FFuel}\right) \\ \le \eta_{p,\ t}^{Fuel\_max} \qquad \forall\ (p \in P, t \in T)\end{gathered} \tag{21}$$

$$\eta_{o,q,t}^{Fr\_\min} \le \sum_i \sum_l F_{i,l,q,t}^{Fr\_dem} - \sum_i \sum_l \sum_j F_{i,l,j,t}^{Fr\_excess} \le \eta_{o,q,t}^{Fr\_\max} \qquad \forall\ (o \in O, q \in Q, t \in T). \tag{22}$$

Existence of processing and purification technologies: the processing and purification technologies j and k, respectively, depend on binary variables ($y_{j,l}$ and $y_{k,m}$) that determinate their existence. In this case, Equations (23) and (24) indicate that only one technology can be installed in each location.

$$\sum_j y_{j,l} \le 1 \qquad \forall\ (l \in L) \tag{23}$$

$$\sum_k y_{k,m} \le 1 \qquad \forall\ (m \in M) \tag{24}$$

3.2. Economic Model

The revenues associated with the sale of products are given by Equations (25)–(27). Each amount of product is multiplied by sale price parameter. Where $R_{k,p,t}^{Bgp}$, $R_{i,q,t}^{Fr}$ and $R_{p,t}^{FFuel}$ are the respective sale price parameters used in the energy equation.

$$PBgRevenue = \sum_{k}\sum_{m}\sum_{p}\sum_{t}\left(R_{k,p,t}^{Bgp} \times F_{k,m,p,t}^{Bgp\_dem}\right) \times H^{Bgp} \times \rho^{Bg\_N} \tag{25}$$

$$DigestateRevenue = \sum_{i}\sum_{l}\sum_{q}\sum_{t}\left(R_{i,q,t}^{Fr} \times F_{i,l,q,t}^{Fr\_dem}\right) \tag{26}$$

$$FFuelRevenue = \left(\sum_{p}\sum_{t} R_{p,t}^{FFuel} \times F_{p,t}^{FFuel\_dem}\right) \times H^{FFuel} \tag{27}$$

The cost associated with biomass purchase, transportation, capital, and operations are calculated by Equations (28)–(31). The biomass purchase, transportation, and operational costs are obtained by the product between the amounts of raw material and products times a unit cost (C^{Bm}, C^{Trans} and $C^{Var.Prod}$), while the capital cost is calculated using a binary variable that decides if the technology is installed or not and using an annualization factor.

$$PurchBmCost = \sum_{i}\sum_{f}\sum_{l}\sum_{t}\left(C_{i,f,t}^{Bm} \times F_{i,f,l,t}^{Bm}\right) \tag{28}$$

$$\begin{aligned} TransCost = & \sum_{i}\sum_{f}\sum_{l}\sum_{t}\left(C_{i,f,l,t}^{Trans,Bm} \times F_{i,f,l,t}^{Bm}\right) + \sum_{i}\sum_{l}\sum_{m}\sum_{t}\left(C_{i,l,m,t}^{Trans,Bg} \times F_{i,l,m,t}^{Bg}\right) \\ & + \sum_{k}\sum_{m}\sum_{p}\sum_{t}\left(C_{k,m,p,t}^{Trans,Bgp} \times F_{k,m,p,t}^{Bgp\_dem}\right) \\ & + \sum_{i}\sum_{l}\sum_{q}\sum_{t}\left(C_{i,l,q,t}^{Trans,Fr} \times F_{i,l,q,t}^{Fr\_dem}\right) \end{aligned} \tag{29}$$

$$CapitalCost = K \times \left[\sum_{j}\sum_{l}\sum_{t}\left(C_{j,l}^{Fix,\ Prod\_tech} \times y_{j,l}\right) + \sum_{k}\sum_{m}\sum_{t}\left(C_{k,m}^{Fix,\ Pur\_tech} \times y_{\ k,m}\right)\right] \tag{30}$$

$$\begin{aligned} OpCost = & \sum_{i}\sum_{l}\sum_{j}\sum_{t}\left(C_{l,j,t}^{Var,Prod\_tech} \times F_{i,l,j,t}^{Bm\_conv}\right) \\ & + \sum_{i}\sum_{m}\sum_{k}\sum_{t}\left(C_{m,k,t}^{Var,Pur\_tech} \times F_{i,m,k,t}^{Bg\_conv}\right) \end{aligned} \tag{31}$$

The annualization factor (K), of processing and purified technologies j and k, respectively, is determined by Equation (30), where α is the discount rate used to determine the annual cost and N is the expected lifetime for each technology.

$$K = \left[\frac{(1+\alpha)^{N} \times \alpha}{(1+\alpha)^{N} - 1}\right] \tag{32}$$

3.3. GHG Emissions

The GHG emissions generated by using fresh fuel are presented in Equation (33).

$$FFuelEmission = E^{Use,FFuel} \times H^{FFuel} \sum_{t} F_{t}^{FFuel\_Total} \quad \forall\ s \tag{33}$$

3.4. Objective Functions

The objective function is formulated for three different cases to compare the effect of the positive or negative monetization on GHG emissions versus a multi-objective strategy that aims to obtain better solutions minimizing the emissions and maximizing the profit. Before explaining the cases, it is necessary to clarify that the total GHG emissions generated by the proposed system are the GHG emissions only generated by the burn of fresh fuel (Equation (34)) because the biogas emissions are not considered. Then, the formulation for the objective function for each case is given as follows.

$$TotalGHG = FFuelEmission \quad (34)$$

Case 1. The first case seeks to maximize the total profit (Equation (35)) making a competition between biogas and fresh fuel. The biogas production is stimulated through carbon emission tax. Then, it is expected that the GHG emissions can decrease due to a penalization on the GHG emissions generated by fresh fuel. Table 1 presents the values of carbon emission tax used in each scenario of this case. The carbon emission taxes vary substantially, from less than 1 € ton^{-1} CO_2eq to a maximum of 126 € ton^{-1} CO_2eq depending on country policies [12]. For this reason, Table 1 shows values in this range.

$$\begin{aligned} TotalProfit = \; & PBgRevenue + DigestateRevenue + FFuelRevenue \\ & -(PurchBmCost + TransCost + CapitalCost + OpCost) \\ & -CTax(TotalGHG) \end{aligned} \quad (35)$$

Table 1. Cost per ton of CO_2eq in carbon emission tax (Case 1).

Scenario	1	2	3	4	5	6	7
Cost CO_2eq (€/ton)	8.93	13.39	22.32	28.57	36.61	46.43	100

Case 2. The second case seeks to maximize the total profit (Equation (36)) stimulating the biogas production through carbon-emission trading (i.e., to give more competitiveness with an economic incentive to the biogas under the fresh fuel and in consequence to have a reduction of GHG emissions). Table 2 presents the values of carbon-emission trading used in each scenario of this case. The carbon emission trading values vary substantially, from less than 1 € ton^{-1} CO_2eq to a maximum of 110 € ton^{-1} CO_2eq depending on country policies. For this reason, Table 1 shows values in this range. The value of 200 € ton^{-1} CO_2eq corresponds to an extreme value only to analyze the behavior of the implementation of this scheme.

$$\begin{aligned} TotalProfit = \; & PBgRevenue + DigestateRevenue + FFuelRevenue \\ & - (PurchBmCost + TransCost + CapitalCost + OpCost) \\ & + CTrad\left(GHG^{UB} - TotalGHG\right) \end{aligned} \quad (36)$$

Table 2. Price per ton of CO_2eq in carbon emission trading (Case 2).

Scenario	1	2	3	4	5	6	7
Price CO_2eq (€/ton)	2.68	8.93	13.39	26.78	71.43	107.14	200

Case 3. This last case aims to maximize the profit and minimize the GHG emissions simultaneously. Equation (37) formulates the multi-objective modelling approach where *FO* is the multi-objective solution and it is equal to the difference among the total profit and the total emissions multiplied by a parameter M. The total profit can be set up using Case 1 or Case 2 or without carbon taxes and trading. Here, M_1 and M_2 are arbitrary values assigned to the objectives to make them of the same order of

magnitude. To obtain M_1 and M_2, first, it is necessary obtain the maximum value of the total profit and the total emissions. Once they were obtained, it is assigned the value of $M = 1$ to the higher one and FO will be taken as zero only for calculating the other M from Equation (37) in this way both total profit and total emissions will be in the same order of magnitude and finally FO can be maximized or minimized. Therefore, since the environmental term in the formulation is negative, if FO is maximized then the profit will be maximized and the GHG emissions will be minimized. Although there are other multi-objective modelling approaches, such as e-constrained, goal programming, multi-stakeholder, etc., this approach was chosen due to the difficulty to obtain the maximum and minimum limits of the economic and environmental objectives (the limits change in every scenario).

$$FO = M_1 \times TotalProfit - M_2 \times TotalGHG \quad (37)$$

4. Case Study

To demonstrate the applicability of the proposed model formulation, 40 cities of Mexico located in the west central region have been selected. The biomass sources are restricted to three: cow manure, organic waste, and wastewater. The case study considers the implementation of three biodigester types: chamber-floating drum type biogas plant, digester-floating drum type biogas holder and fixed-dome type biogas plant. Five upgrading technologies were selected for purified biogas: pressure swing adsorption (PSA), high pressure water scrubbing (HPWS), organic physical scrubbing (OPS), chemical scrubbing process (CSP) and membrane separation (MS). LPG is taken as fresh fuel. Detailed information about the economic, environmental and general parameters, the demand of energy, digestate and biomass availability is presented in the supplementary material with its respective references [16,22,24,36–44].

5. Results and Discussion

The model was coded in the software GAMS [44], where the solver CPLEX was used to solve the associated mixed-integer linear programing problem (MILP). The problem consists of 1,110,112 continues variables, 2240 binary variables and 250,672 single equations. The model was solved 60 times in a computer with Intel® Core™ i7 processor at 2.5 Hz with 8 GB of RAM in 1.92 min of mean CPU time for each solution (scenario) of case study with a standard deviation of 0.16 min. In this section, the discussion of the results is given as follows.

Figure 4 shows reference values without considering taxes, incomes due to generation of GHG emissions and the multi-objective function. The analysis corresponds to maximize the profit for sales of biogas and LPG considering that the energy demand is satisfied 10%, 20%, 50% and 100% for each town in the studied geographical region by either biogas or LPG. For the case of LPG, to obtain the annual incomes and GHG emissions, the amount of biogas demanded by the market is fixed to zero ($F^{Bgp\_dem}_{k,m,p,t} = 0$), then only Equations (20), (21), (27) and (33) are activated in the model formulation. In the case of biogas, the amount of fresh fuel demanded in the market is fixed to zero ($F^{FFuel\_dem}_{p,t} = 0$) and then all equations related to LPG are deactivated. The annual incomes by sales of LPG are 29.66, 59.32, 148.30 and 296.59 million euros for 10, 20, 50, and 100% of energy demands, respectively. The sale price of LPG in the market is about 18.47 €GJ^{-1} [16] with a profit of 60% on sale price. With respect to incomes generated by the sales of biogas, if the sale price of biogas is taken to be at least of 18.47 €GJ^{-1} in order for the biogas to be competitive in a LPG market, Figure 4 shows that the annual profits are 27.69, 48.81, 49.30, and −176.21 million euros for the energy demand respectively. These values represent the 93.34%, 82.28%, 33.24% and −59.41% of the annual profit obtained by the LPG. It means that satisfying a small demand implies a greater benefit due to the selected technologies for producing and upgrading biogas being smaller, and therefore the capital costs being minimized. Otherwise, the capital costs increase to the technologies with a higher capacity, and the transportation costs are higher. The GHG emissions for the biogas supply chain are zero in agreement with the problem statement. For the LPG, the annual GHG emissions are 174.49, 348.99, 872.47, and 1744.95 kton CO_2eq, respectively.

The values mentioned previously will be taken as reference values to analyze the behavior of the biogas supply chain for the proposed cases in order to propose a solution that makes the biogas competitive in a LPG market traying to obtain the best economic and environmental benefits. It is necessary to emphasize that an analysis of the production of digestate might be considered in future works since an excess of this byproduct exists in all cases. Figure 5 shows the excess of digestate produced when 10%, 20%, 50%, and 100% of energy demand is satisfied. The amounts of digestate are in excess are 20.53, 37.48, 66.14 and 69.23 kton per year. The difference when the energy demand is satisfied in 50% and 100% is small about 3.09 kton (i.e., the biomass taken to produce biogas has different yield), and to satisfy 100% the biomass with more yield is chosen while for 50% the biomass with less yield it is selected, and also due to biomass availability in each location. It should be noted that while biogas production exists, digestate will also be produced which could lead to a difficult management provided that a market for this product is not large enough. Therefore, it is necessary to analyze alternative strategies for a good management of this byproduct.

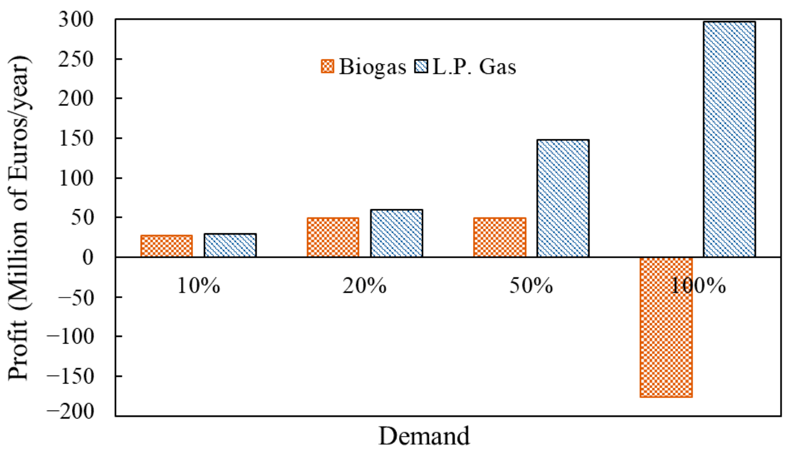

Figure 4. Profit comparison between biogas and LPG to satisfy an energy demands of the studied geographical region.

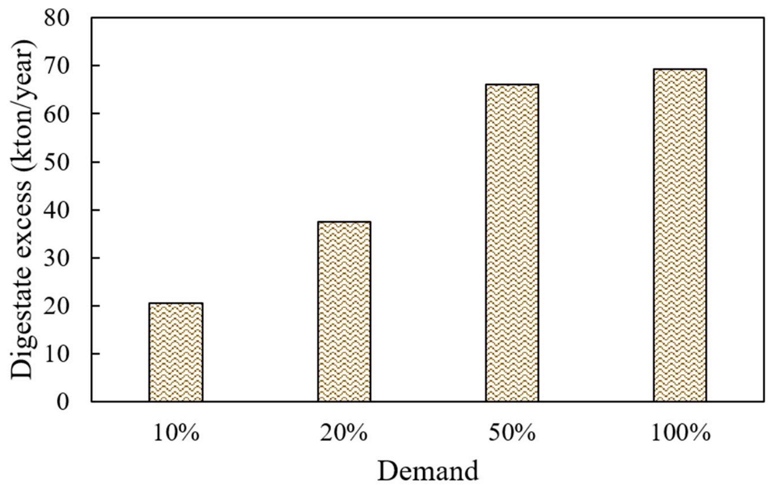

Figure 5. Digestate generated in excess by the biogas supply chain to different energy demand of the studied geographical region.

Figure 6 presents the solution for Case 1, where the objective function takes into consideration the carbon-emission tax (Equation (35)). The problem is solved for different costs of carbon tax (Table 1) maximizing the profit for a satisfaction of energy demand of 10%, 20%, 50% and 100%. The blue column represents the profit and green line represents the GHG emissions. In this case, the energy demand can be satisfied by biogas and LPG simultaneously. Nevertheless, the objective is to motivate the biogas production to decrease the GHG emissions. Due to there being a competition between biogas and LPG, at first LPG is more attractive economically than biogas, then carbon tax stimulates biogas production to the point of the biogas being more attractive economically. As can be seen, for 10% of energy demand, the carbon tax in the Scenario 1 (8.93 € ton^{-1} CO_2eq) does not have influence in the GHG emission mitigation; moreover, when the carbon tax increases in Scenarios 2–7 (8.93 to 100 € ton^{-1} CO_2eq) there is a decrease in the carbon dioxide but the profits are lower. The trend behavior states that to reach a decrease of GHG emissions, it is necessary to have larger carbon taxes and the annual emissions are 174.49, 74.75, 59.72, 14.76, and 46.21 kton CO_2eq with annual profits of 28.10, 27.38, 27.38, 27.18, 27.03, 27.07, 26.93 million euros, respectively, and these values represent 0%, 57%, 66%, 70%, 74%, 82%, and 91% (from 10%) of energy demand replaced by biogas. It should be noticed that the percentage of biogas that can be replaced is calculated with respect to GHG emission reduction because 100% of biogas substitution represents the minimum value of emissions (zero) in agreement with how the GHG emissions were founded in the previous section for both fuels and therefore, the biogas substitution can be easily viewed by the green line (emissions) in Figure 6. For 20%, 50% and 100% of energy demand, it is necessary to use higher values of carbon taxes reaching a maximum 81%, 57% and 40% of energy demand replaced by biogas with the proposed carbon taxes, and to stimulate the biogas production it is necessary to have values of carbon tax of 22.3, 28.57, and 36.61 € ton^{-1} CO_2eq, respectively. However, the incentive to replace LPG is small because when the energy demand percentage increases the difference in profit between biogas and LPG is also increased, as shown in Figure 4. It should be noticed that Scenario 7 (100 € ton^{-1} CO_2eq), in 10% of energy demand will represent a good configuration of the biogas supply chain since it has a good GHG emission mitigation although with low incomes. In addition, it requires a larger carbon tax, which is a penalization that is hard to pay, especially in countries with low economic resources. Regarding energy demands greater than 10%, Regarding is even more difficult. Therefore, the CT scheme as procedure to stimulate competition between biogas and LPG is limited to high penalizations— at least that is how the case is presented.

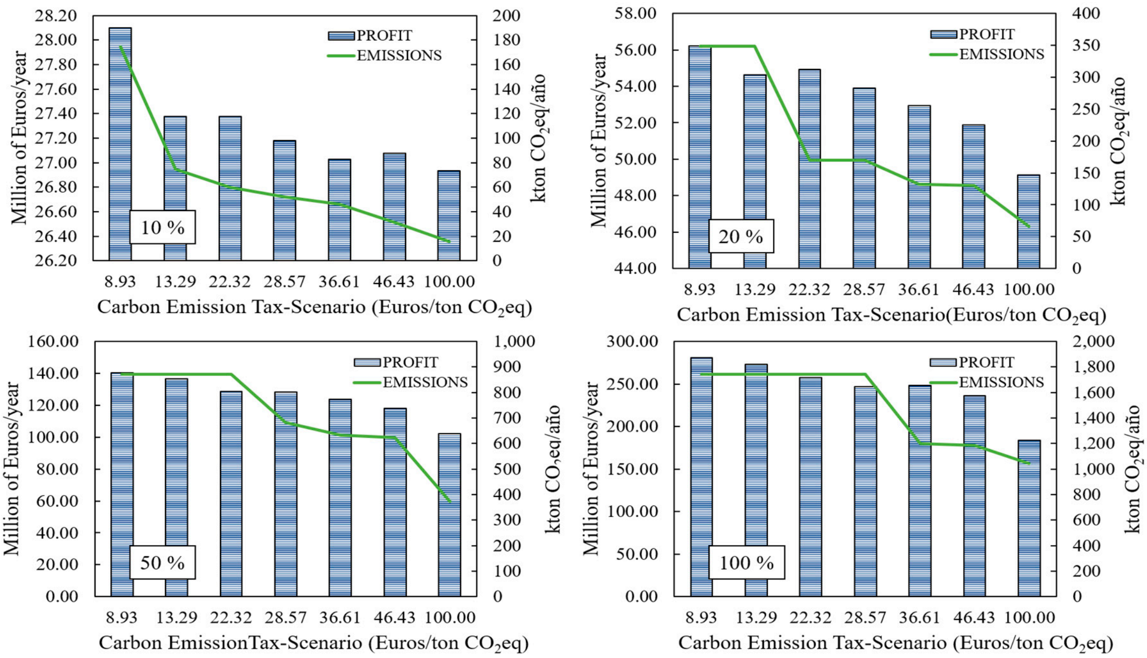

Figure 6. Results for carbon - emission tax scheme using the scenarios from Table 1 to satisfy 10%, 20%, 50% and 100% of energy demand (Case 1).

For Case 2, Figure 7 presents the solution when ETS is considered in the objective function (Equation (36)). Just as in Case 1, the problem is solved for different prices for carbon-emission trading for 10%, 20%, 50%, 100% of energy demand as shown in Table 2. The blue column represents the profit, and the green line represents the GHG emissions. For 10% of the energy demand, when carbon emissions have a price between 2.68 and 8.93 € ton^{-1} CO_2eq, to invest in a biogas project is not convenient, so the GHG emissions remain in the maximum value (i.e., the biogas project is not profitable because the incentives are not enough to give competitiveness to biogas versus LPG (Figure 4)); when the price is 13.39 € ton^{-1} CO_2eq, the profit is kept but the GHG emissions decrease to 74.75 kton CO_2eq, which represents 57% (from 10%) of energy demand replaced by biogas. For 20% of energy demand, values of carbon-emission trading fewer than 26.78 CO_2eq do not stimulate the biogas production because if energy demand is incremented and major infrastructure to produce biogas is needed, it makes biogas less competitive with respect to LPG. In the same way, it occurs for 50% and 100% of energy demand. On the other hand, to decrease GHG emissions to the minimum value (i.e., using the maximum production of biogas and to avoid the using of LPG), a price per ton higher than 200 € ton^{-1} CO_2eq is necessary at least to satisfy 10% and 20% of energy requirements. However, in this scenario (200 € ton^{-1} CO_2eq), 67% and 42% of energy demand is barely replaced by biogas when it is necessary to satisfy 50% and 100% of energy requirements. In general, to stimulate the biogas production, it is necessary to have values of carbon-emission trading of at least 13.39, 26.78, 71.43, and 71.43 € ton^{-1} CO_2eq, for 10%, 20%, 50% and 100% of energy demand, respectively. To achieve the minimum emissions, carbon emission trading values higher than 200 € ton^{-1} CO_2eq are required. Given that carbon-emission trading represents an economic bonus, it could appear that higher values of carbon trading are easily obtained; Nevertheless, this is also limited by the country's policies where the maximum economic bonus by saving GHG emissions is 110 € ton^{-1} CO_2eq, and, moreover, not all countries have the economic potential to offer higher values of carbon-emission trading. Therefore, it is necessary to develop strategies that lead to the mitigation of GHG emissions with lower economic incentives.

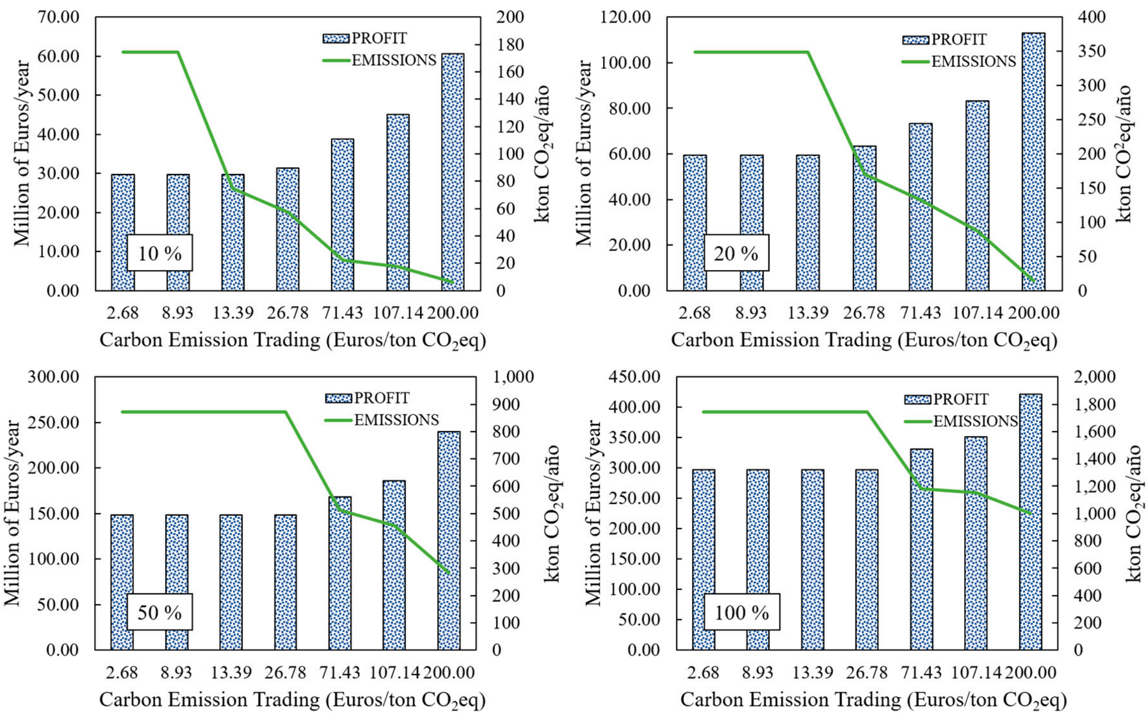

Figure 7. Results for carbon-emission trading using the scenarios from Table 2 to satisfy 10%, 20%, 50% and 100% of energy demand (Case 2).

In both previous cases, the objective is to stimulate biogas production using an economic bonus or an economic sanction (i.e., to have an incentive with purpose of governments or producers of LPG investing in a biogas project with economic and environmental benefits). Then, Case 1 and Case 2 show that it is feasible to stimulate the generation of biogas in competition with the LPG because incentives (taxes or bonus) lead to biogas obtaining higher profit than that obtained without incentives. However, the incentives depend on environmental policies in each country, and these incentives could be difficult to implement. Therefore, in Case 3, it is expected that the incentive values can be improved with respect to the values used in Case 1 and Case 2 using a multi-objective formulation approach for the economic and environmental functions (i.e., maximizing the profit and at the same time minimizing the GHG emissions and then finding a better value of incentives).

Figure 8 displays the results of maximizing the solution in the multi-objective formulation (FO) presented in Equation (37). The solution strategy was to find the value of parameter M_2 that equalizes the environmental function in order of magnitude to the value of the maximum profit for each percentage analyzed. According to the extreme solutions obtained when the LPG is only sold (see Table 3), $M_1 = 1$ and $M_2 = 170$ (explanation of how these parameters are obtained is made in the model formulation section). Therefore, since the environmental term in the formulation is negative, if FO is maximized then the profit will be maximized and the GHG emissions will be minimized and consequently the incentive can be calculated to obtain at least the economic benefit when there is only sale of LPG (i.e., to obtain the same economic benefit with biogas). The maximum economic benefit by LPG can be seen in Figure 4. In the graph (Figure 8) the solutions obtained for each percentage of energy demand are presented. The light column represents the profit using the multi-objective formulation with the benefit obtained by the carbon-ETS and the GHG emissions generated are represented by the dashed green line. To make a comparison with the methodology used in Case 2, the values of profit and GHG emissions were calculated using the values of ETS calculated in Case 2; In the figure, the dark column represents the profit and the GHG emissions are represented by the continuous line.

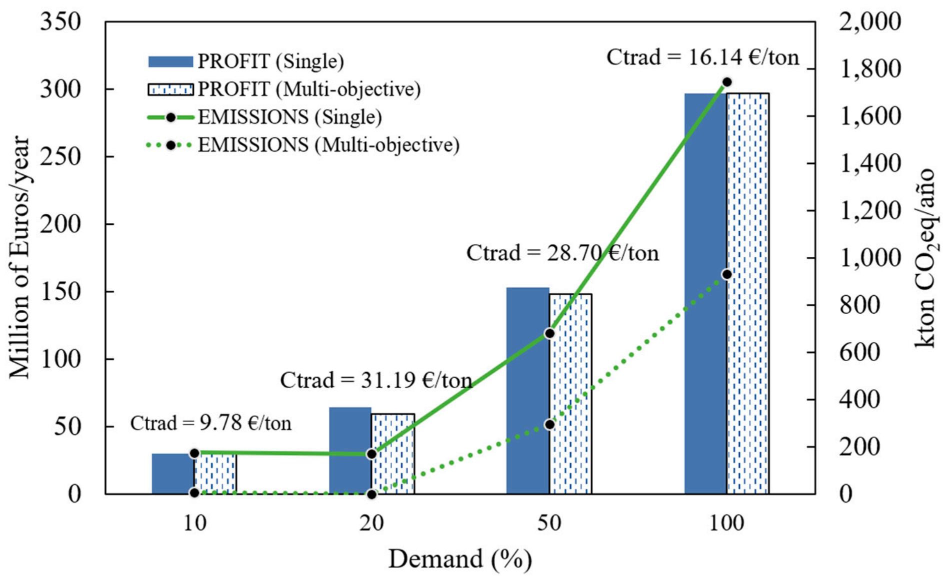

Figure 8. Results for multi-objective formulation using carbon emission trading (Case 3).

The annual profit values obtained by the maximization to FO are 26.66, 59.32, 148.30, and 296.59 million euros with their respective GHG emissions of 7.03, 0.37, 293.96, and 931.06 kton CO_2eq for 10%, 20%, 50% and 100% of energy demand satisfied. The broken-down results are shown in Table 3, where the biogas and LPG revenues, purchasing biomass costs, transportation cost, capital, and operational costs are presented. The obtained annual profits, in comparison with the profit and GHG emissions obtained when only LPG is used to satisfy the energy demand, are in the same magnitude because the values of the carbon-emission trading are obtained to accomplish at least the profit of LPG. For each percentage of energy demand, the values of carbon-emission trading with the multi-objective formulation are 9.78, 31.19, 28.70, and 16.14 € ton^{-1} CO_2eq, respectively. In general, these carbon incentives are lower than the values that stimulate the biogas production in Case 2 where the carbon incentives are at least 13.39, 26.78, 74.43, and 74.43 € ton^{-1} CO_2eq with their respective annual GHG emissions of 74.75, 170.11, 512.95, and 1182.02 kton CO_2eq (see Figure 7) for each percentage of energy demand. Therefore, there is an appreciable reduction of the values of carbon-emission trading and GHG emissions. However, it is necessary to compare the solution obtained by Case 3 and Case 2 in a specific manner (i.e., using the values of carbon-emission trading obtained by Case 3 in Case 2). This way, it can be analyzed which formulation is better.

Table 3. Broken-down results for multi-objective formulation.

	Demand (%)			
	10	20	50	100
Total Profit (€/year)	29,658,797.20	59,316,072.60	148,289,586.00	296,584,072.00
Total Revenue	50,823,297.20	111,023,472.60	233,047,986.00	406,027,972.00
Biogas Supply Chain	47,991,000.00	100,090,000	166,470,000.00	234,640,000.00
Carbon Emission Trading	1,637,797.20	10,870,594.30	16,613,986.00	13,137,972.00
LPG	1,194,500.00	62,878.30	49,964,000.00	158,250,000.00
Total Cost	21,164,500.00	51,707,400.00	84,758,400.00	109,443,900.00
Biomass Cost	982,400.00	2,380,100.00	4,623,400.00	7,282,900.00
Transportation Cost	2,212,000.00	8,570,300.00	15,086,000.00	13,763,000.00
Capital Cost	5,752,100.00	15,178,000.00	22,704,000.00	28,561,000.00
Operational Cost	12,218,000.00	25,579,000.00	42,345,000.00	59,837,000.00
Total Emissions (Ton CO_2eq/year)	7027.62	369.94	293,960.00	931,060.00
LPG				
Total Profit (€/year)	29,658,797.16	59,317,594.32	148,293,985.8	296,587,971.60
Total Emissions (Ton CO_2eq/year)	174,494.99	348,989.99	872,474.99	1,744,949.98

Using the same values of carbon-emission trading, for both Case 2 and Case 3, Figure 8 shows that the values of 9.78, 31.31, 28.70, and 16.14 € ton^{-1} CO_2eq give annual profits about 29.66, 64.34, 153.20, and 296.60 million euros and annual emissions of 174.50, 170.12, 681.57, and 1744.90 kton CO_2eq to 10%, 20%, 50%, and 100% of energy demand, respectively (using carbon - pricing values of Case 2). Therefore, the graph illustrates the comparison between Case 2 and Case 3 and there is a considerable reduction of GHG emissions and similar profit values with the multi-objective formulation (Case 3). The percentages of reduction of GHG emissions are 95.97%, 99.78%, 56.87%, and 46.64% while the values of profit in both cases are similar to a difference in percentage of 0.00%, 7.80%, 3.20% and 0.00%, respectively. While a greater reduction of emissions exists, more LPG is replaced by biogas (i.e., the percentages of LPG replaced by biogas are 95.97%, 99.78%, 56.87% and 46.64%), then at 10% and 20% of energy demand, the biogas can practically supply all the demand, however for 50 and 100% of demand, the biogas barely reaches half of energy demand because the ratio between biogas revenues and total cost in the biogas supply chain changes depending on the technology capacity used to produce biogas (ratio: 2.26, 1.93, 1.96, and 2.13, respectively). For example, between the energy demand of 50% and 100%, the revenues/cost ratio are 1.96 and 2.13, reaching 56.87% and 46.64% of replaced LPG because the necessary cost to replace the 50% or 100% increases considerably as Figure 4 shows. Therefore, increasing the energy demand means that technologies with more production capacity, and higher transportation costs are necessary, making the complete biogas substitution not profitable for 50% and 100% of energy demand, at least in the case study analyzed by this work. However, the values of carbon-emission trading obtained by the multi-objective approach are within the limits used around the world (110 € ton^{-1} CO_2eq) and these represent at least 31% of the maximum limit (taking the maximum value by Case 3: 31.19 € ton^{-1} CO_2eq) allowing for the implementation of renewable energy projects in countries with minor economic potential.

Finally, the multi-objective formulation in Case 3 demonstrates that is a better way to stimulate the investment of a biogas project than single-objective formulation using the monetization of carbon-emissions because in the carbon emission tax strategy the profit result is more affected than GHG emissions and when the carbon emission trading is used, as in the emission carbon tax strategy, a very high price is required which will be difficult to reach by some governments. In addition, the model can provide the supply-chain configuration: type of selected biomass, type of production and purification technologies, and the flowrates between locations as has been already been shown in a previous work [32].

6. Conclusions

This paper has presented a MILP optimization formulation for the biogas supply chain to analyze the performance of investing in a biogas project in order to decrease GHG emissions and to obtain at least equivalent profits in comparison with the fuel currently used in the market. The proposed model formulation can be used to solve different case studies using the appropriated data and it can be used as a decision-making tool. A case study was proposed for a geographical region in Mexico to show the effect of carbon emission monetization with the proposed methodology. The results demonstrated that carbon-emission tax or carbon-emission trading are useful methods to stimulate the investment in a biogas project when it is in competition with fossil fuel. It has been shown that high carbon taxes and bonuses are required to reach at least the same profits and then to make a reduction of GHG emissions. However, using a multi-objective optimization formulation leads to obtain better solutions using lower values of carbon-emission taxes and carbon-emission trading and reaching optimal profits and higher GHG emissions reduction.

Future works should consider the comparison of detailed analysis of upstream emissions for biogas in competition with others fuels, to demonstrate the potential advantages of renewable energy under conventional energy sources; in this work, upstream emissions were not considered because the main contribution was to demonstrate that a multi-objective optimization formulation in combination with carbon pricing led to better results to stimulate the production of renewable energy. Also, optimization approaches, as with stochastic optimization techniques, could be implemented in order to study the uncertainty associated with the model and evaluate the prospective social, economic, and environmental benefits.

Supplementary Materials: The following data is available online at http://www.mdpi.com/2227-9717/7/10/668/s1: Table S1: Capacity, capital cost and yield of production technologies for biogas, Table S2: Capacity, capital cost and yield of upgrade technologies for biogas, Table S3: Economic parameters for case study, Table S4: Environmental and general parameters for case study, Table S5: Demands and availability for case study, Table S6: Selected technologies for 10% of energy demand in case study.

Author Contributions: Methodology L.A.D.-T. and J.T.-F.; Conceptualization F.N.-R. and J.M.P.-O.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Indices

f	locations where biomass can be purchased; $f \in F$
i	biomass types; $i \in I$
j	technologies for production of biogas; $j \in J$
k	technologies for purification of biogas; $k \in K$
l	locations where processing technologies for biomass can be installed; $l \in L$
m	locations where purification technologies for biogas can be installed; $m \in M$
o	digestate types; $o \in O$
p	markets for biogas $p \in P$
q	market for digestate; $q \in Q$
t	time periods; $t \in T$

Variables

$F^{Bm}_{i,f,l,t}$	amount of biomass type i purchased from supply source f and transported to location l at period t (ton)
$F^{Bg}_{i,l,j,t}$	amount of biogas type i produced in location l with technology j at period t (Nm^3)
$F^{Bm\_conv}_{i,l,j,t}$	amount of biomass type i to be converted in location l with technology j at period t (ton)
$F^{Fr}_{i,l,j,t}$	amount of digestate from biomass type i produced in location l with technology j at period t (ton)
$F^{Bg}_{i,l,m,t}$	amount of biogas type i produced in location l and transported to location m at period t (Nm^3)
$F^{Fr\_dem}_{i,l,q,t}$	amount of digestate from biomass type i in location l to be sold in market q at period t (ton)
$F^{Fr\_excess}_{i,l,j,t}$	amount of digestate excess from biomass type i produced in location l with technology j at period t (ton)
$F^{Bg\_Total}_{i,l,t}$	total amount of biogas type i generated in location l at period t (Nm^3)
$F^{Bm\_Total}_{i,l,t}$	total amount of biomass type i in location l at period t (ton)
$F^{Fr\_Total}_{i,l,t}$	total amount of digestate from biomass type i generated in location l at period t (ton)
$F^{Bg\_conv}_{i,m,k,t}$	amount of biogas type i to be converted in location m with technology k at period t (Nm^3)
$F^{Bgp}_{i,m,k,t}$	amount of purified biogas type i in location m using technology k at period t (Nm^3)
$F^{Bg\_conv\_Total}_{i,m,t}$	total amount of biogas type i to be converted in location m at period t (Nm^3)
$F^{Fr\_dem\_Total}_{i,q,t}$	total amount of digestate from biomass type i to be sold in market q at period t (ton)
$F^{Bgp\_dem}_{k,m,p,t}$	amount of purified biogas type k from location m to be sold in market p at period t (Nm^3)
$F^{Bgp\_Total}_{k,m,t}$	total amount of purified biogas type k generated in location m at period t (Nm^3)
$F^{Bgp\_dem\_Total}_{k,p,t}$	total amount of purified biogas type k to be sold in market p at period t (Nm^3)
$F^{FFuel\_dem}_{p,t}$	amount of fresh fuel in market p at period t (ton)
$F^{FFuel\_Total}_{t}$	total amount of fresh fuel at period t (ton)
CapitalCost	capital costs associated with processing and purification technologies for each scenario s (€/year)
DigestateRevenue	revenues associated with sale of digestate (€/year)
FFuelEmission	GHG emissions of fresh fuel (ton^{-1} CO_2eq/year)
FFuelRevenue	revenues associated with sale of fresh fuel (€/year)
FO	multi-objective function
GHG	GHG emissions (ton^{-1} CO_2eq/year)
OpCost	operational costs associated with processing and purification technologies for each scenario s (€/year)
PBgRevenue	revenues associated with sale of purified biogas for each scenario s (€/year)
PurchBmCost	costs associated with biomass purchase for each scenario s (€/year)
TotalGHG	total emissions (ton^{-1} CO_2eq/year)
TransCost	costs associated with transportation of biomass, biogas and biofertilizer in supply chain for each scenario s (€/year)

Binary Variables

$y_{j,l}$	binary variable for the existence of processing technology j in location
$y_{k,m}$	binary variable for the existence of purification technology k in location

Parameters

H^{Bgp}	heating value for fresh fuel (GJ/ton)
H^{FFuel}	heating value for fresh fuel (GJ/ton)
γ^{Bg}_{j}	capacity of technology j to produce biogas (Nm^3/month)
γ^{Fr}_{j}	capacity of technology j to produce digestate (ton/month)
γ^{Bgp}_{k}	capacity of technology k to produce purified biogas (Nm^3/month)
$\eta^{Fr}_{o,q,t}$	demand for digestate type o in market q at period t (ton)
$\eta^{Fuel}_{p,\ t}$	energy demand for purified biogas or fresh (GJ)

ρ^{Bg_N}	normal density for purified biogas (Ton/Nm^3)
$\chi_{i,j}^{Bg}$	efficiency factor to produce biogas type i in technology j (Nm^3/ton of biomass input)
$\chi_{i,j}^{Fr}$	efficiency factor to produce biofertilizer type i in technology j (ton/ton of biomass input)
$\chi_{i,k}^{Bgp}$	efficiency factor to produce purified biogas from biogas type i in technology k (Nm^3/Nm^3)
$\vartheta_{i,f,t}^{Bm}$	availability of biomass type i in supply source at period t (ton)
Economic parameters	
$C_{i,f,l,t}^{Trans,Bm}$	cost associated with transportation of biomass type i from supply source f to location l at period t (€/ton)
$C_{i,f,t}^{Bm}$	st associated with purchase and pre-processing of biomass type i in supply source f at period t (€/ton)
$C_{i,l,m,t}^{Trans,Bg}$	cost associated with transportation of biogas type i from location l to location m at period t (€/Nm^3)
$C_{i,l,p,t}^{Trans,Bg}$	cost associated with transportation of biogas type i from location l to market p at period t (€/Nm^3)
$C_{i,l,q,t}^{Trans,Fr}$	cost associated with transportation of digestate type i from location l to market q at period t (€/ton)
$C_{j,l}^{Fix,\ Prod\_tech}$	fixed cost associated with the processing technology j in location l (€)
$C_{k,m,p,t}^{Trans,Bgp}$	cost associated with transportation of purified biogas type k from location m to market p at period t (€/Nm^3)
$C_{k,m}^{Fix,\ Pur\_tech}$	fixed cost associated with the purification technology k in location m (€)
$C_{l,j,t}^{Var,Prod\_tech}$	variable cost associated with the processing technology j in location l at period t (€/ton)
$C_{m,k,t}^{Var,Pur\_tech}$	variable cost associated with the purification technology k in location m at period t (€/Nm^3)
$R_{i,q,t}^{Fr}$	price of digestate type i in market q at period t (€/ton)
$R_{k,p,t}^{Bgp}$	price of purified biogas type k in market p at period t (€/GJ)
$R_{p,t}^{FFuel}$	price of fresh fuel in market p at period t (€/GJ)
K	factor for annualize fixed costs of technologies j and k
N	project lifetime (year)
α	interest rate of processing technology j and k
Environmental parameters	
$E^{Use,FFuel}$	GHG emissions generated by using fresh fuel (ton CO_2-eq/GJ)
Superscripts	
Bg	biogas
Bgp	purified biogas
Bm	biomass
EQ	equality condition
FFuel	fresh fuel
Fix	fixed
Fr	digestate
N	normal
Prod	production
Pur	purification
Total	total
Trans	transportation
UB	upper bound
Var	variable
conv	conversion
dem	demand
max	maximum
min	minimum
tech	technology

References

1. United Nations Transforming our World: The 2030 Agenda for Sustainable Development. Available online: https://sustainabledevelopment.un.org/index.php?page=view&type=400&nr=2125&menu=1515 (accessed on 28 May 2019).
2. Hoegh-Guldberg, O.; Jacob, D.; Taylor, M.; Bindi, M.; Brown, S.; Camilloni, I.; Diedhiou, A.; Djalante, R.; Ebi, K.L.; Engelbrecht, F.; et al. Impacts of 1.5 °C Global Warming on Natural and Human Systems. In *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*; Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., et al., Eds.; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2018.
3. Newell, R.G.; Jaffe, A.B.; Stavins, R.N. The effects of economic and policy incentives on carbon mitigation technologies. *Energy Econ.* **2006**, *28*, 563–578. [CrossRef]
4. Liang, Q.-M.; Yao, Y.-F.; Zhao, L.-T.; Wang, C.; Yang, R.-G.; Wei, Y.-M. Platform for China Energy & Environmental Policy Analysis: A general design and its application. *Environ. Model. Softw.* **2014**, *51*, 195–206.
5. Baranzini, A.; van den Bergh, J.C.J.M.; Carattini, S.; Howarth, R.B.; Padilla, E.; Roca, J. Carbon pricing in climate policy: Seven reasons, complementary instruments, and political economy considerations. *Wiley Interdiscip. Rev. Clim. Chang.* **2017**, *8*, e462. [CrossRef]
6. Xu, X.; Xu, X.; He, P. Joint production and pricing decisions for multiple products with cap-and-trade and carbon tax regulations. *J. Clean. Prod.* **2016**, *112*, 4093–4106. [CrossRef]
7. Du, S.; Tang, W.; Song, M. Low-carbon production with low-carbon premium in cap-and-trade regulation. *J. Clean. Prod.* **2016**, *134*, 652–662. [CrossRef]
8. Zakeri, A.; Dehghanian, F.; Fahimnia, B.; Sarkis, J. Carbon pricing versus emissions trading: A supply chain planning perspective. *Int. J. Prod. Econ.* **2015**, *164*, 197–205. [CrossRef]
9. Chiu, F.-P.; Kuo, H.-I.; Chen, C.-C.; Hsu, C.-S. The energy price equivalence of carbon taxes and emissions trading—Theory and evidence. *Appl. Energy* **2015**, *160*, 164–171. [CrossRef]
10. Cui, L.-B.; Fan, Y.; Zhu, L.; Bi, Q.-H. How will the emissions trading scheme save cost for achieving China's 2020 carbon intensity reduction target? *Appl. Energy* **2014**, *136*, 1043–1052. [CrossRef]
11. Li, W.; Jia, Z. Carbon tax, emission trading, or the mixed policy: Which is the most effective strategy for climate change mitigation in China? *Mitig. Adapt. Strateg. Glob. Chang.* **2017**, *22*, 973–992. [CrossRef]
12. *World Bank and Ecofys State and Trends of Carbon Pricing 2018 (May)*; World Bank: Washington, DC, USA, 2018.
13. Jiang, J.; Xie, D.; Ye, B.; Shen, B.; Chen, Z. Research on China's cap-and-trade carbon emission trading scheme: Overview and outlook. *Appl. Energy* **2016**, *178*, 902–917. [CrossRef]
14. Carl, J.; Fedor, D. Tracking global carbon revenues: A survey of carbon taxes versus cap-and-trade in the real world. *Energy Policy* **2016**, *96*, 50–77. [CrossRef]
15. Raslavičius, L.; Keršys, A.; Mockus, S.; Keršienė, N.; Starevičius, M. Liquefied petroleum gas (LPG) as a medium-term option in the transition to sustainable fuels and transport. *Renew. Sustain. Energy Rev.* **2014**, *32*, 513–525. [CrossRef]
16. Sener, L.P. *Gas Outlook 2016–2030*; Secretaría de Energía: Ciudad de México, Mexico, 2016.
17. COFECE. *Transición hacia Mercados Competidos de Energía: Gas LP*; Cuad. Promoción la Competencia: Cuajimalpa, Ciudad de México, Mexico, 2018.
18. Zhang, B.; Chen, B. Sustainability accounting of a household biogas project based on emergy. *Appl. Energy* **2017**, *194*, 819–831. [CrossRef]
19. Awe, O.W.; Zhao, Y.; Nzihou, A.; Minh, D.P.; Lyczko, N. A Review of Biogas Utilisation, Purification and Upgrading Technologies. *Waste Biomass Valorization* **2017**, *8*, 267–283. [CrossRef]
20. Martín-Hernández, E.; Sampat, A.M.; Zavala, V.M.; Martín, M. Optimal integrated facility for waste processing. *Chem. Eng. Res. Des.* **2018**, *131*, 160–182. [CrossRef]
21. Timonen, K.; Sinkko, T.; Luostarinen, S.; Tampio, E.; Joensuu, K. LCA of anaerobic digestion: Emission allocation for energy and digestate. *J. Clean. Prod.* **2019**, *235*, 1567–1579. [CrossRef]
22. Scarlat, N.; Dallemand, J.-F.; Fahl, F. Biogas: Developments and perspectives in Europe. *Renew. Energy* **2018**, *129*, 457–472. [CrossRef]

23. Kaspersen, B.S.; Christensen, T.B.; Fredenslund, A.M.; Møller, H.B.; Butts, M.B.; Jensen, N.H.; Kjaer, T. Linking climate change mitigation and coastal eutrophication management through biogas technology: Evidence from a new Danish bioenergy concept. *Sci. Total Environ.* **2016**, *541*, 1124–1131. [CrossRef]
24. Ullah Khan, I.; Hafiz Dzarfan Othman, M.; Hashim, H.; Matsuura, T.; Ismail, A.F.; Rezaei-DashtArzhandi, M.; Wan Azelee, I. Biogas as a renewable energy fuel—A review of biogas upgrading, utilisation and storage. *Energy Convers. Manag.* **2017**, *150*, 277–294. [CrossRef]
25. Tovar-Facio, J.; Fuentes-Cortes, L.F.; Ponce-Ortega, J.M. Carbon Price Evaluation in Power Systems for Flaring Mitigation. *J. Sustain. Dev. Energy Water Environ. Syst.* **2019**, *7*, 716–729. [CrossRef]
26. Qiu, Y.; Qiao, J.; Pardalos, P.M. A branch-and-price algorithm for production routing problems with carbon cap-and-trade. *Omega* **2017**, *68*, 49–61. [CrossRef]
27. Fuentes-Cortés, L.F.; Ma, Y.; Ponce-Ortega, J.M.; Ruiz-Mercado, G.; Zavala, V.M. Valuation of water and emissions in energy systems. *Appl. Energy* **2018**, *210*, 518–528. [CrossRef] [PubMed]
28. Fuentes-Cortés, L.F.; Serna-González, M.; Ponce-Ortega, J.M. Analysis of Carbon Policies in the Optimal Design of Domestic Cogeneration Systems Involving Biogas Consumption. *ACS Sustain. Chem. Eng.* **2017**, *5*, 4429–4442. [CrossRef]
29. Gonela, V. Stochastic optimization of hybrid electricity supply chain considering carbon emission schemes. *Sustain. Prod. Consum.* **2018**, *14*, 136–151. [CrossRef]
30. Yu, M.; Cruz, J.M.; "Michelle" Li, D. The sustainable supply chain network competition with environmental tax policies. *Int. J. Prod. Econ.* **2018**. [CrossRef]
31. Bing, X.; Bloemhof-Ruwaard, J.; Chaabane, A.; van der Vorst, J. Global reverse supply chain redesign for household plastic waste under the emission trading scheme. *J. Clean. Prod.* **2015**, *103*, 28–39. [CrossRef]
32. Díaz-Trujillo, L.A.; Nápoles-Rivera, F. Optimization of biogas supply chain in Mexico considering economic and environmental aspects. *Renew. Energy* **2019**, *139*, 1227–1240. [CrossRef]
33. Paolini, V.; Petracchini, F.; Segreto, M.; Tomassetti, L.; Naja, N.; Cecinato, A. Environmental impact of biogas: A short review of current knowledge. *J. Environ. Sci. Heal. Part A* **2018**, *53*, 899–906. [CrossRef] [PubMed]
34. Moro, A.; Lonza, L. Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. *Transp. Res. Part D Transp. Environ.* **2018**, *64*, 5–14. [CrossRef]
35. World LP Gas Association. *LP Gas: An Energy Solution For A Low Carbon World*; Energetics A Subsidiary of VSE Corporation: Paris, France, 2007.
36. Yasar, A.; Nazir, S.; Rasheed, R.; Tabinda, A.B.; Nazar, M. Economic review of different designs of biogas plants at household level in Pakistan. *Renew. Sustain. Energy Rev.* **2017**, *74*, 221–229. [CrossRef]
37. SENER. *Prospectiva de Gas Natural y Gas L.P 2014–2028*; Secretaría de Energía: Ciudad de México, Mexico, 2014.
38. BIRF; AIF; IFC; MIGA; CIADI Banco Mundial. Available. Fertilizer Consumption. Available online: https://datos.bancomundial.org/indicador/AG.CON.FERT.ZS?locations=MX&view=chart (accessed on 24 April 2019).
39. Instituto Nacional de Estádistica y Geografía (México). *Anuario Estadístico y Geográfico de Jalisco 2016*; INEGI: Ciudad de México, Mexico, 2016.
40. Instituto Nacional de Estádistica y Geografía (México). *Anuario Estadístico y Geográfico de Michoacán de Ocampo 2016*; INEGI: Ciudad de México, Mexico, 2016.
41. Instituto Nacional de Estádistica y Geografía (México). *Anuario Estadístico y Geográfico de Guanajuato 2016*; INEGI: Ciudad de México, Mexico, 2016.
42. Waste Protocols Project. *Anaerobic digestate: Partial Financial Impact Assessment of the Introduction of a Quality Protocol for the Production and Use of Anaerobic Digestate*; Enviroment Agency: Oxon, Banbury, UK, 2009.
43. INECC. *Factores de Emisión Para Los Diferentes Tipos de Combustibles Fósiles y Alternativos que se Consumen en México*; SEMARNAT: México, DF, Mexico, 2014.
44. GAMS. Development Corporation General Algebraic Modelling System (GAMS) 2013. Available online: https://www.gams.com/latest/docs/UG_MAIN.html (accessed on 25 April 2019).