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Interdependent Relations Between Agribusiness And Solar Photovoltaic Energy

Moisés Martínez-Soto[1], Carlos Rodríguez-Monroy[2], Eduardo Lemus-León[3], Eveligh Prado-Carpio[4], María de Lourdes Olivo-Garrido[5], Ricardo Hernández-Besembel[6]

[1] *Universidad del Zulia, Maracaibo, Venezuela; e-mail: moisesenriquemartinezsoto@fa.luz.edu.ve*
ORCID 0000-0002-1505-8593
[2] *Universidad Politécnica, Madrid, España; e-mail: cmonroy@etsii.upm.es*
ORCID 0000-0002-3402-1876
[3] *Universidad Simón Bolívar, Facultad de Ingenierías, Cúcuta, Colombia; e-mail: e.lemus@unisimonbolivar.edu.co*
[4] *Universidad Técnica de Machala, Machala, Ecuador; e-mail: eprado@utmachala.edu.ec*
ORCID 0000-0002-2494-9435
[5] *Universidad Central de Venezuela, Caracas, Venezuela; e-mail: lourdes_olivo@yahoo.com*
ORCID 0000-0001-8993-670X
[6] *20 Solar Energy LLC, USA; e-mail: rdohdez@gmail.com*
ORCID 0000-0002-9818-974X

1. Introduction

The energy and food systems are interrelated. On the one hand, about 30% of the world's energy is consumed within agri-food systems, mainly in the post-harvest stage, when fossil fuels are used. On the other hand, energy is also responsible for a third of greenhouse gas emissions in these systems. Both must be transformed to meet the current and future demand for food and energy in a fair, environmentally sustainable, and inclusive manner, directed towards the co-production of these resources (International Renewable Energy Agency- IRENA and Food and Agriculture Organization of the United Nations- FAO, 2021; FAO, 2011).

From another point of view, energy is one of the main variables in the function of agribusiness and one of the fundamental inputs in production systems that focus on higher levels of productivity, competitiveness, and sustainability. According to the Inter-American Institute for Cooperation on Agriculture-IICA (2010), agribusiness can be seen as an integrated business system, where agriculture (plant, animal, aquaculture, and forestry) is considered as a system of value chains centered on meeting consumer demands.

As it is in the public and scientific domain, the world reserves of conventional energy are decreasing, while its global demand is increasing, with the adverse socio-environmental effects that its use entails. In this context, the world's energy and food systems must be transformed to meet the growing demand; be more inclusive, safe, and sustainable; and align with the international agreements and treaties signed by the countries in these matters (IRENA-FAO, 2021).

By 2040, the share of renewable energy in electricity generation is expected to rise from the current 25% to more than 40%. Photovoltaic solar energy has the most significant productive potential of all non-conventional renewable energy sources. The current annual technical potential for electricity generation from solar energy is estimated at 613 Petawatt-hour (PWh) per year (613×10^{12} kWh) (IRENA, 2020; IEA, 2021).

Renewable energy solutions and integrated energy and food production systems represent a trend that can favor the balance between sustainable energy and food security while contributing to job creation, gender equality, resilience, and climate adaptation. This new model integrates solar energy and agriculture and has its most emblematic expression in agrophotovoltaic systems (Velázquez, 2016).

Some of the leading agricultural activities that are favored by photovoltaic (PV) solar energy are water pumping, solar greenhouses, crop drying systems and the development of water purification or desalination plants, soil preparation and its fertilization, animal production, rural infrastructure, the mechanization of agricultural work, intelligent ultrasonic devices to repel insects and the quality of life in rural areas, among others (Van Campen *et al*., 2000; Rashid *et al*., 2017; Saputra *et al*., 2018; García-Marín, 2019; Ranjitha *et al*., 2019; Betanzo Torres *et al.*, 2020).

Thus, there is a trend towards a paradigm shift from the farmer-aquaculturist, producer of food and raw materials for industry, to the farmer who produces energy, as well as food and agro-industrial raw materials, which encourages productive diversification in the field and generation of new sources of income for rural producers. To this end, a joint approach to the energy transition and the transformation of agricultural systems is crucial to meet the Sustainable Development Goals and the Paris Agreement on Climate Change (IRENA-FAO, 2021).

On the other hand, this research on the relationships of interdependence between agribusiness and photovoltaic solar energy is directly linked to two of these objectives of the United Nations Development Program (United Nations Development Program-UNDP, 2020); affordable and clean energy (SDG-7), as well as responsible production and consumption (SDG-12); and indirectly with six other goals: decent work and economic growth (SDG-8); industry, innovation and infrastructure (SDG-9); resilient infrastructures; sustainable industrialization and promotion of innovation; sustainable cities and communities (SDG-11); reduction of inequalities (SDG-10). In this sense, the United Nations Organization (UNO), through Program 21, Chapter 14, establishes as an objective the "Promotion of sustainable agriculture and rural development," being the United Nations' Food and Agriculture Organization (FAO) the coordinating body.

Considering the above, this research aims to analyze the interdependence relationships between agribusiness and photovoltaic solar energy constructs to achieve higher productivity, competitiveness, and sustainability levels.

2. Methodology

The System Dynamics methodology has been used in this research to study the interrelations between the *Agribusiness* and the *Photovoltaic energy* constructs. According to ACT-Innova (2022), System Dynamics is a methodology for constructing simulation models for complex systems, such as those studied by organizational engineering and particularly the present investigation. System Dynamics is applied to the study of unstructured or soft systems.

In System Dynamics, simulation allows numerical integration techniques to obtain trajectories for the variables included in any model. However, these trajectories are never interpreted as predictions but as projections or trends. The primary objective of System Dynamics is to understand the structural causes that induce the behavior of a system through knowledge of each of its constituent elements and the interactions that are generated between them, an approach that is far from the traditional analysis schemes (Forrester, 2003). This understanding should normally develop a clear framework for determining actions to improve the system's operation or solve the observed problems. The advantage of System Dynamics is that these actions can be simulated at a low cost, making it possible to assess their results without putting them into practice in the existing system.

According to Martín (2007), System Dynamics allows the construction of models after a careful analysis of the elements of the system. This analysis enables extracting the internal logic of the model and thereby attempting to understand the long-term evolution of the system. In this case, the adjustment of the model to the historical data occupies a secondary place, being the analysis of the internal logic and the structural relationships in the model the fundamental points of its construction.

A useful sequence of activities for the design and validation of simulation models that have to allow deciding which of several proposals is more efficient to solve the problem is the following:

Create the causal diagram

- Definition of the problem.
- Definition of first, second, and third-order influences.
- Definition of relationships and feedback loops.

Creation of the flow and level diagram

- Characterization of the elements.
- Write equations and assign values to parameters.
- Creation of a first version of the model and its stabilization.
- Identification of the critical elements.
- Simulation and validation.

According to Martín (2007), the software to carry out simulation models applying System Dynamics as a methodology has evolved in recent years in two aspects: to make it more user-friendly, in which the appearance of Windows was fundamental, and another is the continuous increase of the benefits. An example of simulation software for this type of model is Vensim PLE ® v. 5.10, which is used for teaching and research at the Massachusetts Institute of Technology (MIT) business school and has been used in this research. This software is a graphical simulation modeling tool that enables the user to conceptualize, document, simulate, analyze, and optimize System Dynamics models. Vensim provides a flexible and straightforward way to create simulation models, either causal or flow diagrams (Martín-García, 2019). In this research on the interrelationships between agro-industrial constructions and photovoltaic solar systems, only the causal diagram is presented, leaving the flow diagrams for later stages.

Causal loop diagrams or influence diagrams are so named because each connection shows a causal relationship. The creation of the causal diagram presents the following sequence of steps: definition of the problem, determination of the components of the system, the definition of first-, second-, and third-order influences, the definition of relationships, identification of feedback loops, filtering of non-relevant influences and proposal of possible solutions to the problem.

3. Results and discussion

Photovoltaic systems in the agricultural sector are intended to provide electrical energy to diversified agricultural production processes, such as vegetable, animal, aquaculture, and forestry, to which agroenergy production can now be added. The aim is to improve productivity, competitiveness, and sustainability of agribusiness, following the 2030 Agenda for Sustainable Development and the Paris Agreement on Climate Change (IRENA-FAO, 2021).

Implementing photovoltaic systems in agricultural production units for agribusiness development constitutes a paradigm shift in the energy-agriculture relationship. Farms can be transformed from net consumer units to farms capable of achieving self-sufficiency and even selling surplus to the local power grid. This can produce savings in the energy costs of the production processes and even generate additional income through possible sales of the surplus energy produced. In this sense, solar energy could have a favorable impact on agricultural production, based on the *sui generis* classification (Table 1) carried out in this research on the situation of the conventional electric power service and the motivations that agricultural producers could have install photovoltaic systems in their farms.

Table 1. Classification of the power service and motivation of agricultural producers to install a photovoltaic system on the farm

Type of power service of the agricultural production unit (Current situation)	Power service characteristics	Motivation for installing photovoltaic systems (Expected situation)
Reliable and expensive power service	High quality and reliable service but with high prices	Cost reduction / Attain greater security of supply when generating its own power
Defective power service	Poor quality and unreliable. It presents frequent or potential failures damaging the production processes	Improve the quality and reliability of the power supply to improve the production processes
No power available	No power suppliers exist	Count on the necessary power supply to develop more intensely the productive processes
Any of the preceding	Inexistent, expensive or defective service	Additional income

Source: Authors

Based on this classification of the characteristics of the local electricity service, a causal diagram (Figure 1) has been developed in which the interdependence relationships between the *Agribusiness* and *Photovoltaic Energy* constructs are presented and analyzed through the *Diversified Agro-production* construct.

3.1. Problem Definition

The problem under study is to determine the existing gap in productivity, competitiveness, and sustainability between conventional agro-industries and productive units that do not have photovoltaic energy systems and the new agro-industries and productive units that generate their electricity through photovoltaic systems. In some cases, they generate surpluses injected into the electrical network as a new element of diversification of their productive system, based on the four types of production units and their relationship with the local electrical system.

3.2. Determination of the components of the causal model, their integration, and relationships

In this research, the primary constructs analyzed are Photovoltaic Energy, Diversified Agroproduction, and Agribusiness. These variables were selected based on the review of the literature and the experience of the researchers.

Photovoltaic systems are made up of solar panels and solar components (including inverters, batteries, regulators, optimizers, solar structures, and all hardware necessary for the solar system to function optimally), solar information and communication technologies (ICTs, which include the software that integrates the equipment and systems as a whole within the photovoltaic system and its link with agroproduction). This construct and its components are influenced by the characteristics of the local electrical network.

Diversified agro-production is a construct that is made up of the variables agricultural inputs, agricultural hardware, agricultural infrastructure, and agricultural ICTs. It includes food production, raw materials for industry, and agroenergy production.

The *Agribusiness* construct in this research represents a balanced integration of the productivity, competitiveness, and sustainability that agribusiness can achieve in its interaction with diversified agricultural production and photovoltaic energy.

In addition, there are two secondary constructs. In a positive sense, the *Dynamizing* construct, among which the processes of Knowledge Management and Appropriate Public Policies stand out in a positive sense. The *Photovoltaic Conflicts* construct is made up of Photovoltaic Waste, Conflicts over Land Use, and Overexploitation of Aquifers in a negative sense.

All these constructs, components, and elements that make up the relationships of interdependence, both positive and negative, between agribusiness and photovoltaic solar energy can be seen in Figure 1.

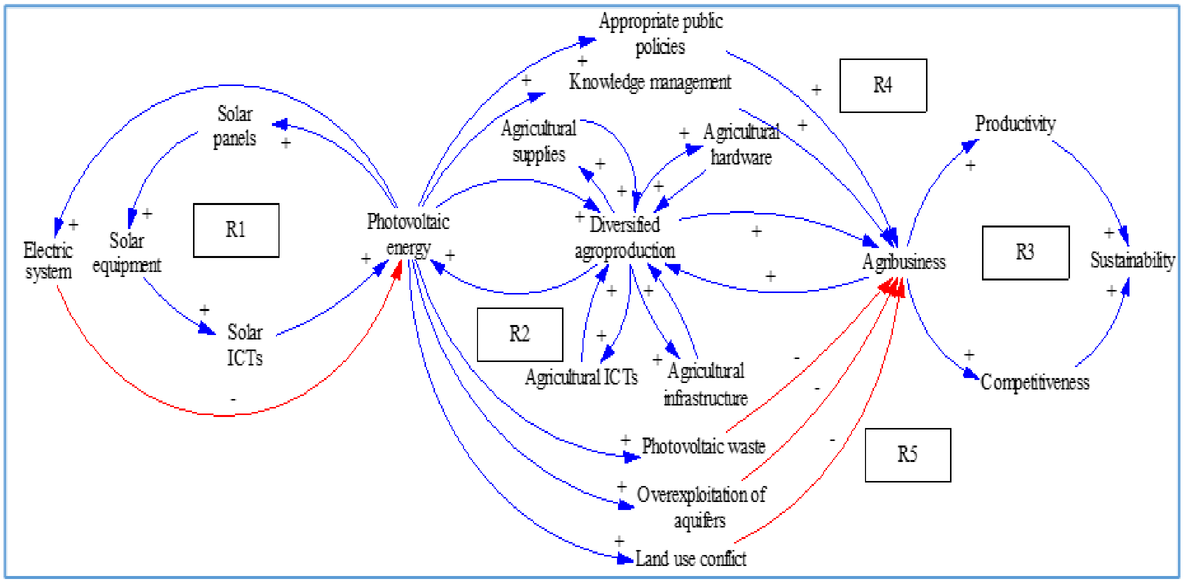

Figure 1. Causal diagram of the interdependence relationships between agribusiness and photovoltaic solar energy

Source: Authors

In this causal diagram, the primary constructs comprise three groups of loops or constructs. The R1 group or *Photovoltaic Energy* construct loops (on the left), the R2 group or *Diversified Agroproduction* construct loops (in the center), and the R3 group or *Agribusiness* construct loops (on the right). In addition, two constructs or groups of secondary loops are also identified in the causal diagram. They are the R4 group or *Dynamizing* construct loops (at the top), and the R5 group or *Photovoltaic Conflicts* construct loops (at the bottom). These five constructs or loop groups are briefly described, analyzed, and discussed in the following sections.

3.3. The R1 group of loops or the *Photovoltaic Energy* construct loops

The **R1 group of loops** or the *Photovoltaic Energy* construct comprises solar panels, solar equipment, and solar ICT. It originates in an unsatisfactory local electrical service or in a satisfactory electrical service in a productive unit interested in diversifying its activity by incorporating the agroenergy sector to have a new source of income or reduce its energy costs. Thus, it can achieve higher productivity, competitiveness, and sustainability. If the local electrical system provides satisfactory service to the production units reliably and reasonably priced, installing photovoltaic equipment will not be necessary.

Figure 2 shows how the first-order influences (those that directly modify the behavior of the problem under study. Second-order influences modify first-order influences, and so on for third-order and fourth-order influences, if any) of the *Photovoltaic Energy* construct are, firstly, the local electricity service itself, whose relationship is inverse (Figure 1). This means that the customers of the electricity service who are less satisfied with it are more likely to install photovoltaic plants in their production units. On the contrary, those clients satisfied with the local electrical service will not be interested in installing photovoltaic systems in the agricultural production units. Then we observe that the supply of photovoltaic energy that begins with the photoelectric effect of the solar panels is in direct relation, which expresses that the greater the photovoltaic energy, the greater the power and number of solar panels required. Finally, the very development of the *Diversified Agroproduction* construct, whose relationship is also direct, indicates that the greater the latter's growth, the greater the development of the *Photovoltaic Energy* construct. This is also influenced in the second-order by the *Agribusiness* construct, which is interpreted as follows: the more significant the development of the *Agribusiness* construct, the greater the development of the *Diversified Agroproduction construct*, so the *Photovoltaic Energy* construct will increase.

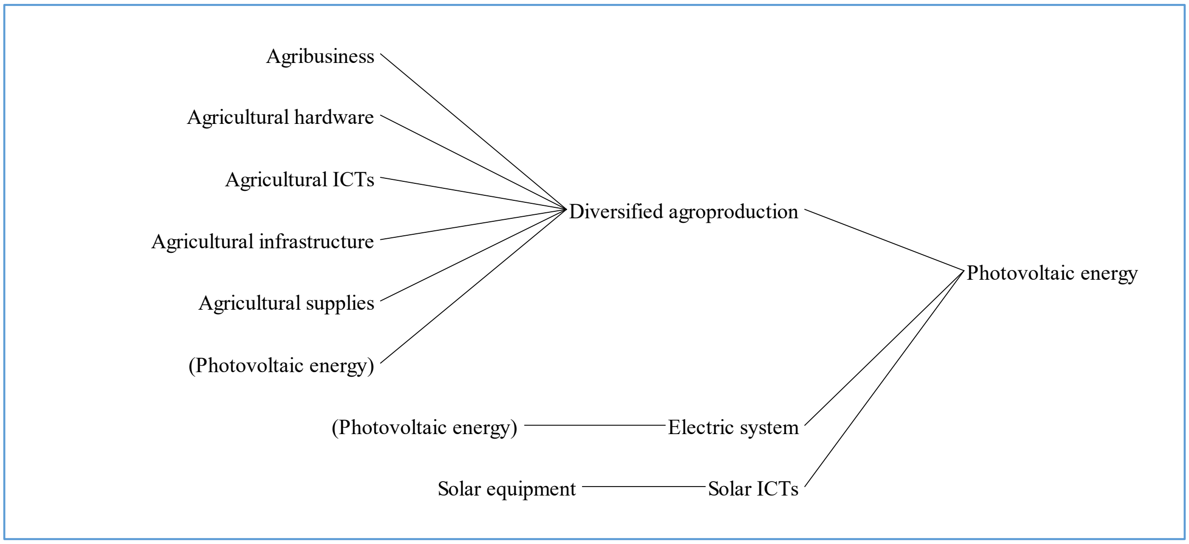

Figure 2. Tree of causes of the *Photovoltaic Energy* construct

Source: Authors

Once the production unit decides to install a photovoltaic power plant, the first elements are the solar panels that convert solar energy into direct current electric power through the photoelectric effect. This direct current (DC) electrical energy is sent to the solar equipment, among which the inverters that transform it into alternating current (AC) electric power stand out. This AC energy is used in the production units by lights, electric pumps, milk coolers, electric mills, or other AC electrical equipment used in agricultural production units (Table 2, Loop Number 3). Another option is that DC electrical energy is used directly in agricultural equipment that operates with DC, such as the case of DC irrigation pumps, also called solar irrigation pumps, or in electric tractors.

In this research, as indicated in previous paragraphs, solar equipment is understood as the entire set of hardware used in the solar energy industry, including inverters, batteries, regulators, optimizers, support structures, wiring, screws, and all physical elements related to its operation. To which must be added electrical equipment that works with DC, such as solar irrigation pumps, which favor irrigation tasks, especially in areas with no power lines.

Table 2. The R1 group of loops of the *Photovoltaic Energy* construct

Loop Number 1 of length 1 (-) Photovoltaic energy Electric system **Loop Number 2 of length 1 (+)** Photovoltaic energy Diversified agroproduction **Loop Number 3 of length 3 (+)** Photovoltaic energy Solar panels Solar equipment Solar ICTs **Loop Number 4 of length 3 (+)** Photovoltaic energy Appropriate public policies Agribusiness Diversified agroproduction **Loop Number 5 of length 3 (-)** Photovoltaic energy Land use conflict Agribusiness Diversified agroproduction	**Loop Number 6 of length 3 (+)** Photovoltaic energy Knowledge management Agribusiness Diversified agroproduction **Loop Number 7 of length 3 (-)** Photovoltaic energy Photovoltaic waste Agribusiness Diversified agroproduction **Loop Number 8 of length 3 (-)** Photovoltaic energy Overexploitation of aquifers Agribusiness Diversified agroproduction

Source: Authors

Another component of the photovoltaic loop is represented by the information and communication technologies applied in the solar energy industry that integrate the components, the diversified agricultural production, and agribusiness. The market offers software and monitoring elements for photovoltaic systems and their integration with the electrical network. They allow monitoring of photovoltaic electricity production, the electricity consumption of the production unit, the amount of energy stored in batteries, and everything that requires electricity within the production unit. This software performs calculations of money to be paid or received and carbon emissions avoided due to the solar energy activities.

In another sense, Figure 3 shows the tree of consequences of the *Photovoltaic Energy* construct. Here we observe the positive and first-order influence on the *Diversified Agro-production* construct and subsequently on the *Agribusiness* construct. Therefore, we infer a relationship of interdependence between these three primary constructs of the causal model (Figure 1) (Huang and Chang, 2021).

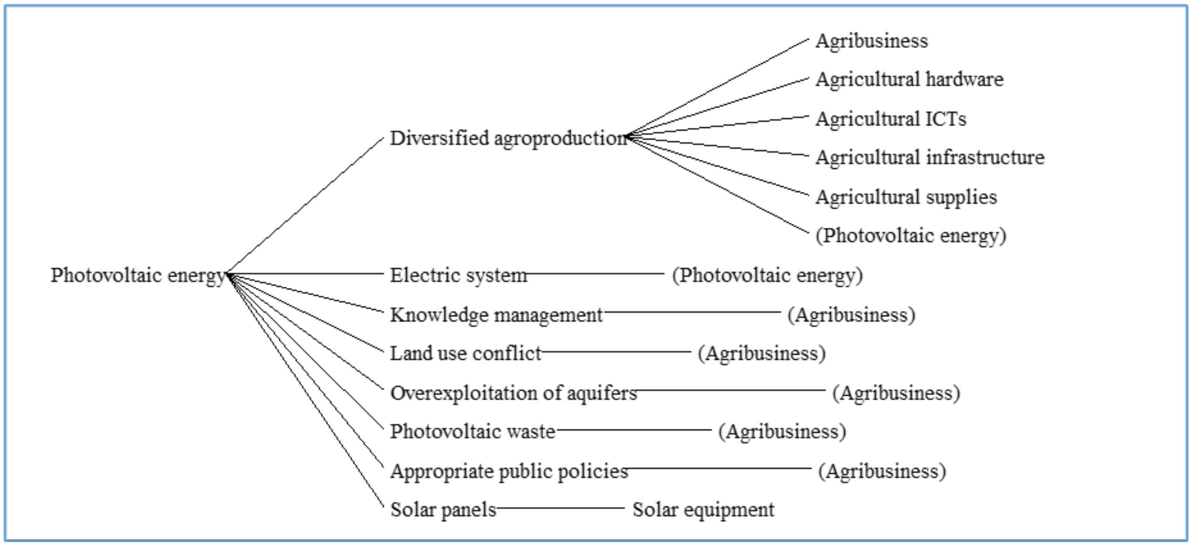

Figure 3. Tree of consequences of the *Photovoltaic Energy* construct

Source: Authors

Similarly, we observe how the *Photovoltaic Energy* construct has a positive and first-order influence on the local electrical network, as well as on the components of the *Dynamizing* construct, namely appropriate public policies and knowledge management (Martínez-Soto, 2011; Morris-Díaz, 2014), as well as on the *Photovoltaic Conflicts* construct integrated by photovoltaic waste, overexploitation of aquifers and conflicts over land use. The relationship of the *Photovoltaic Energy* construct is positive and direct with all these components. This means that the greater the development of the *Photovoltaic Energy* construct, the greater the development of photovoltaic public policies, knowledge management, and innovation in this industry, as well as the growth of conflicts due to the amount of photovoltaic waste that will be produced, and the overexploitation of aquifers used to irrigate crops due to the abundant and cheap energy (FAO, 2018). Finally, conflicts over the use and occupation of land will also increase (Prados-Velasco, 2010).

Secondly, the influence of the *Photovoltaic Energy* construct on the elements of the *Dynamizing* constructs favors the development of the *Agribusiness* construct if appropriate public policies and knowledge management in innovation advance adequately in the countries, regions, and localities where the photovoltaic energy plants are being installed.

On the contrary, if these public policies are not favorable and there is no mechanism to transmit knowledge assets related to photovoltaic technology, then the development of the *Agribusiness* construct will be slow or even harmful.

The *Photovoltaic Energy* construct will also have a second-order influence on the *Agribusiness* construct through the *Photovoltaic Conflict* construct. In this case, the relationship is inverse due to the negative effect of photovoltaic waste, overexploitation of aquifers used in irrigation, and finally, conflicts over land use. If these elements increase, agribusiness and photovoltaic generation will be negatively affected.

Regarding the group of feedback loops related to the *Photovoltaic energy* construct, it was determined, according to what is observed in Figure 3 presented above, that it has eight feedback loops, four positive and four negative, which allows inferring that the flows and levels model to develop will be balanced.

3.4. The R2 group of loops of the *Diversified Agroproduction* construct

The R2 group of loops of the *Diversified Agroproduction* construct has as main elements that integrate and cause it the agricultural inputs, the agricultural hardware, the agricultural infrastructure, and the agricultural ICTs. Reference is made to the new elements emerging as part of the interaction between photovoltaic energy, diversified agroproduction, and agribusiness (Figure 1).

In the case of agricultural inputs, the relationship is direct. The development of new photovoltaic agricultural inputs will influence the *Diversified Agroproduction* construct. The new photovoltaic input is precisely the electrical energy of photovoltaic origin that is cheaper and sufficient for developing the agroproductive process. Electric power is one of the inputs that have the most influence on production processes, according to the four types of electric service described in Table 1 at the beginning of the analysis of the results. Figure 4 shows the tree of causes of the *Diversified Agroproduction* construct.

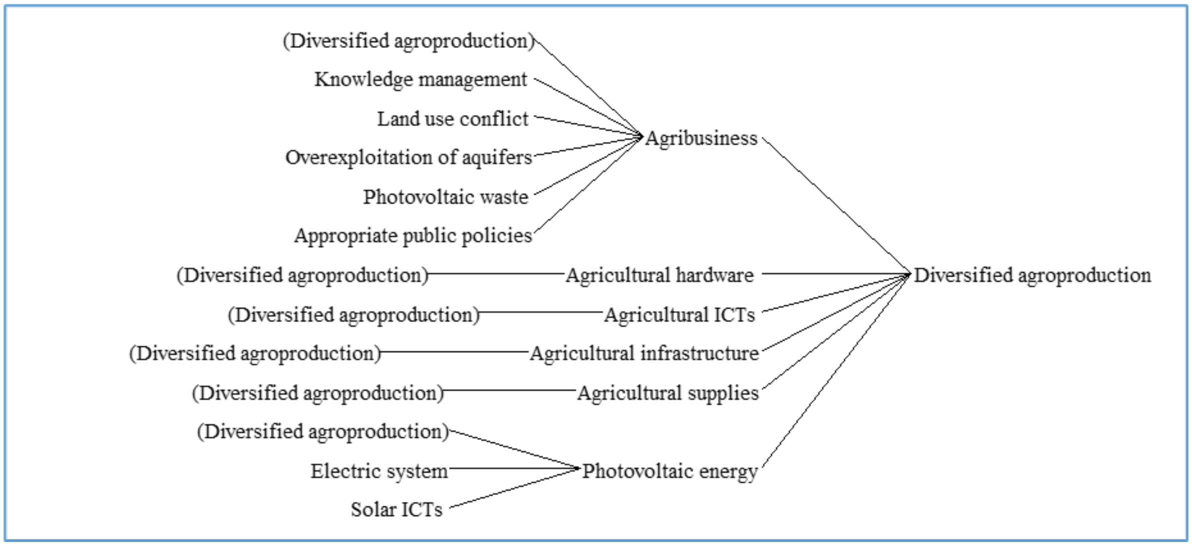

Figure 4. Tree of causes of the *Diversified Agroproduction* construct

Source: Authors

Low-cost electrical energy, sufficient for developing the production process, provides better management conditions for plants and animals. For example, in a poultry farm for fattening broilers, the controlled environments of temperature, lighting, air quality, and automatic drinkers and feeders require a significant amount of energy per animal, which can be supplied in conditions of competition by photovoltaic energy. Likewise, this occurs in the case of greenhouses for crops such as tomatoes and many others. In other words, energy would no longer be a limiting input in production, thus fulfilling the Liebig Minimum Law for agricultural production, which states that the growth of the agricultural output is not controlled by the total resources available but by the scarcest resource.

The agricultural hardware elements are integrated by all the equipment used in the agricultural production units, modernizing or adapting to the new reality of photovoltaic energy within the productive system. Such is the case of the advancement of electric tractors offered in the market and their possibility of massive entry into production units. Their use is related to obtaining abundant electrical energy at competitive prices, which could be stimulated by the prospect of generating power to energize these tractors (Xue, 2017a).

Likewise, developing a new solar-type agricultural infrastructure will also significantly influence conventional production systems. Irrigation systems with pumps that consume much energy and represent an operating expense are a significant example. Solar pumping systems are already offered on the market, with submersible direct current pumps capable of irrigating crop fields in areas that do not have power lines. These systems can also contribute to energizing the pumps in conventional irrigation systems with power lines, but what is required is to reduce the electricity bill. Other commercially used examples are solar electric fences to facilitate rotational grazing, water supply systems in drinking fountains with solar pumping, energy-intensive poultry, and pig farms, and photovoltaic systems that partially supply the energy consumed.

Another symbolic element to consider is developing the agrophotovoltaic concept, in which solar panels and crops share the same space on agricultural land (Xue, 2017b). In this case, the shade that the solar panels project on the vegetable crops can become an element that affects the conventional way of producing since the shade influences the physiology of the crop. We can generate a new microclimate by shades and diffusion of light within the crop field. A similar effect could occur in large pools dedicated to aquaculture production, for example, shrimp, due to the impact of full or partial shade and oxygenation that the floating structures of the panels could provide. Solar panels are also influenced by new transparent designs that allow light beams of a specific wavelength to pass through them to plants and algae. At the same time, the photoelectric effect uses other wavelengths to produce electricity.

Finally, agricultural ICTs will also be affected and, at the same time, will influence the *Diversified Agroproduction*, which is expanding with the development of software in the fields of farm administration, management of irrigation systems in greenhouses, and management of photovoltaic systems. These systems can be integrated to provide multiple utilities to monitor, improve, and make innovative modifications in production systems. Among the most important is having real-time information on photovoltaic energy production and consumption, the supply and consumption of water in greenhouses, and the physical and economical production of a particular item, allowing managers, technicians, and agricultural workers to know the evolution of the process in real-time, to make appropriate decisions and act accordingly.

These four elements: inputs, hardware, software, and solar infrastructure, have a direct and positive influence on the *Diversified Agroproduction* construct, which feeds back through each case. In other words, the greater the development of inputs, hardware, software, and infrastructure, the greater the evolution of the *Diversified Agroproduction* construct and vice versa.

The *Diversified Agroproduction* construct is placed between the *Photovoltaic Energy* and *Agribusiness* constructs, interacting with both. On the one hand, it is influenced by the type of photovoltaic system that the production unit has and, on the other hand, by the characteristics of agribusinesses and their levels of productivity, competitiveness, and sustainability (Proctor *et al.*, 2021). There can be production units oriented to plant, animal, aquaculture, and forestry ítems, or comprehensive, multipurpose farms to produce food or raw materials for agribusiness, which will develop with agroenergy production a new business line. That will help strengthen their market position while complying with the production matrix's decarbonization and sustainable development goals. This issue of the decarbonization of the agricultural energy matrix will probably influence the decision of consumers to purchase food products in the future, gaining this type of product a greater reputation and prestige in the markets.

The consequences of the *Diversified Agroproduction* construct are observed in Figure 5. The positive and direct first-order relationship with the Agribusiness construct and the positive and direct second-order relationship with the elements of competitiveness and productivity stand out. This allows us to infer that an increase in the *Diversified Agroproduction* construct will increase the *Agribusiness* construct and its levels of competitiveness and productivity.

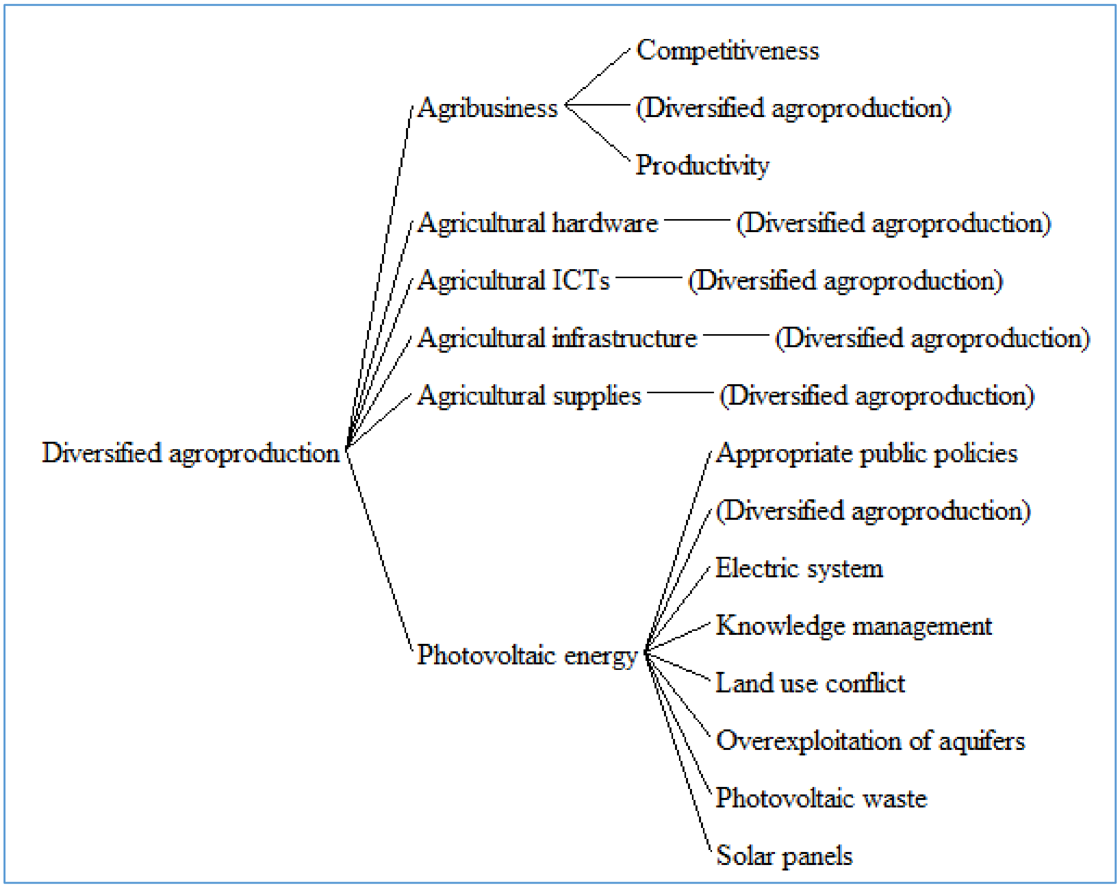

Figure 5. Tree of consequences of the *Diversified Agroproduction* construct

Source: Authors

The *Diversified Agroproduction* construct has eleven feedback loops, as shown in Table 3. Of these, eight are positive and three negative. Those analyzed in more detail in this section, specifically loops 2, 3, 4, and 5, are related to supplies, infrastructure, agricultural software, and agricultural hardware infrastructure.

Table 3. The R2 group of loops of the *Diversified Agroproduction* construct

Loop Number 1 of length 1 (+)	**Loop Number 8 of length 3 (-)**
Diversified agroproduction	Diversified agroproduction
Photovoltaic energy	Photovoltaic energy
Loop Number 2 of length 1 (+)	Overexploitation of aquifers
Diversified agroproduction	Agribusiness
Agricultural supplies	**Loop Number 9 of length 3 (-)**
Loop Number 3 of length 1 (+)	Diversified agroproduction
Diversified agroproduction	Photovoltaic energy
Agricultural infrastructure	Land use conflict
Loop Number 4 of length 1 (+)	Agribusiness
Diversified agroproduction	**Loop Number 10 of length 3 (+)**

Agricultural ICTs **Loop Number 5 of length 1 (+)** Diversified agroproduction Agricultural hardware **Loop Number 6 of length 1 (+)** Diversified agroproduction Agribusiness **Loop Number 7 of length 3 (-)** Diversified agroproduction Photovoltaic energy Photovoltaic waste Agribusiness	Diversified agroproduction Photovoltaic energy Knowledge management Agribusiness **Loop Number 11 of length 3 (+)** Diversified agroproduction Photovoltaic energy Appropriate public policies Agribusiness

Source: Authors

3.5. The R3 group of loops of the *Agribusiness* construct

The R3 group of loops of the *Agribusiness* construct is the third component presented and analyzed. It is also the most important of this research since the problem under study is the gap in agribusiness performance of the production units that have solar power as support for their production systems versus those that do not.

Among the first-order causes of the *Agribusiness* construct, the *Diversified Agroproduction* construct with a direct and positive relationship stands out. Other relevant influences are the elements of appropriate public policies and knowledge management of the *Dynamizing* construct, with a direct and positive relationship, and the *Photovoltaic Conflict* construct that integrates the elements for land use, photovoltaic waste, and overexploitation of aquifers. These three elements have an inverse and negative relationship (Figure 6). These relationships have already been discussed in the previous sections.

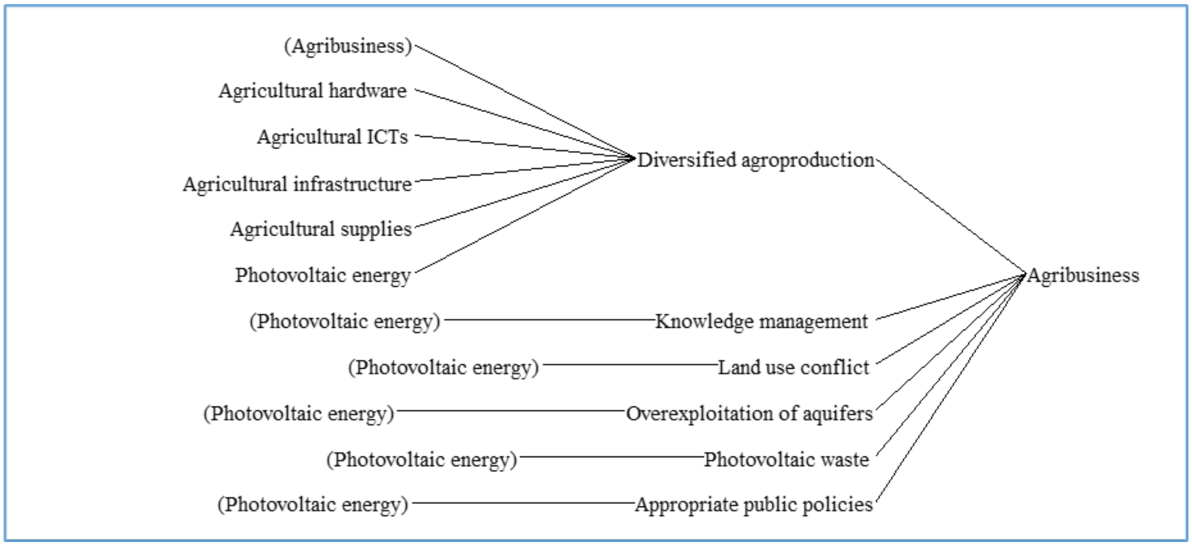

Figure 6. Tree of causes of the *Agrobusiness* construct

Source: Authors

As noted above, in this research, photovoltaic agribusinesses are defined as the balanced integration of the productivity, competitiveness, and sustainability variables and their interaction with diversified agroproduction and photovoltaic energy. Below is a brief outline of the elements mentioned.

Productivity, competitiveness, and sustainability are part of the tree of consequences of the *Agribusiness* construct, as shown in Figure 7. In this figure, the positive and direct first-order relationship between the *Agribusiness* construct and the productivity and competitiveness elements can be identified, as well as a positive and direct second-order relationship with the sustainability element, the latter being the essential quality to develop within the causal model, for an agricultural production unit.

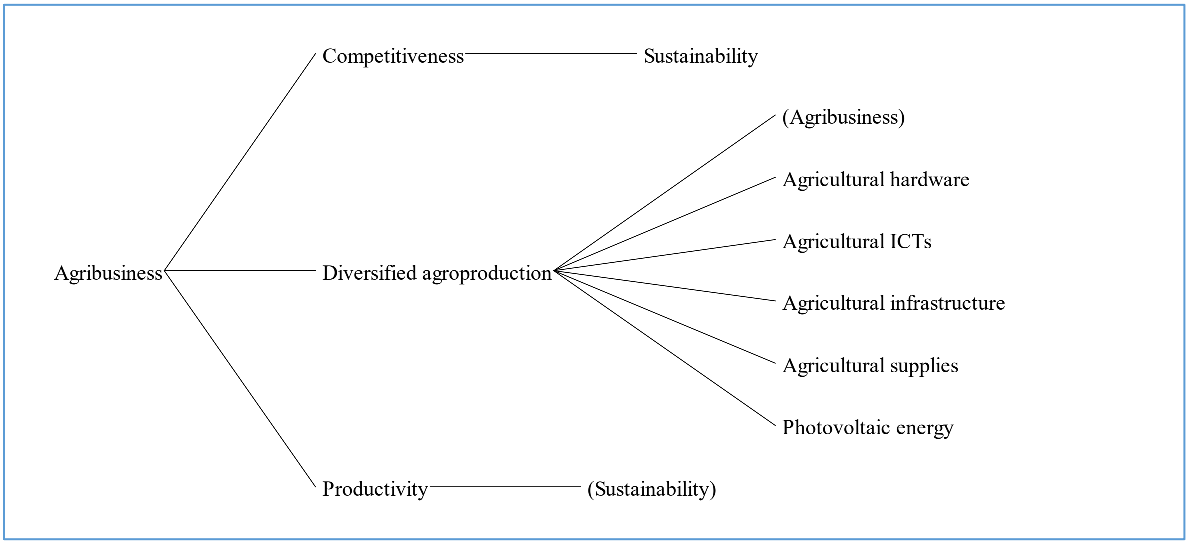

Figure 7. Tree of consequences del *Agribusiness* construct

Source: Authors

The productivity element is the efficiency with which production processes are developed in an agricultural system. This efficiency can be evaluated in physical terms or economic terms. In physical terms, efficiency can be measured through indicators such as the yield in tons per hectare of a crop such as tomatoes, liters of milk per hectare or per cow per day on a cattle farm, or tons of shrimp per hectare in aquaculture pools. However, the land resource, measured in hectares, could also be replaced by the energy resource and measured in kWh, calculating the amount of agricultural product per 1 kWh of energy applied to production. This process would allow agricultural managers and researchers to have new management indicators that integrate farm and energy production. Likewise, efficiency can be measured in economic terms through widely used indicators, such as profitability, cost-benefit ratio, unit production costs, and utility.

The competitiveness element is defined in this research as the possibility that the products generated by photovoltaic-supported *diversified agroproduction* enable production units to position themselves with an advantage in the markets. This can be achieved either because they are less expensive, of higher quality with more added value, or they dominate specific market segments, such as food, agricultural raw materials, or energy. In these three aspects, *diversified agroproduction* could expand its participation in the markets if it genuinely succeeds in significantly reducing energy production costs while increasing physical productivity. Markets are becoming increasingly aware of the need to consume products with a lower carbon footprint. These items reach higher prices in specific market segments, such as the ecological markets. Likewise, the photovoltaic electrical energy produced within the agricultural production unit could be more attractive in terms of safety, accessibility, and economy compared to that of the conventional electrical network.

Finally, the sustainability element is defined in this research as the possibility of agribusiness to endure over time by having economic, social, and environmental viability, which must be developed continuously and permanently facing the challenges and opportunities that said dynamic offers. In economic terms, *diversified agroproduction* supported by photovoltaic energy would last over time based on its favorable effects on productivity and competitiveness. In social terms, this interaction between photovoltaic energy and agribusiness could generate better quality food products at lower prices, benefitting large sectors of the population with food insecurity due to more difficult access to such goods. Furthermore, in environmental terms, viability could be achieved if the energy matrix is effectively decarbonized and the carbon footprint of the agricultural products it offers is reduced. To conclude, the *Agribusiness* construct has six feedback loops, three positive and three negative, as shown in Table 4.

Table 4. The R3 group of loops of the *Agribusiness* construct

Loop Number 1 of length 1 (+) Agribusiness Diversified agroproduction **Loop Number 2 of length 3 (+)** Agribusiness Diversified agroproduction Photovoltaic energy Appropriate public policies **Loop Number 3 of length 3 (-)** Agribusiness Diversified agroproduction Photovoltaic energy Photovoltaic waste	**Loop Number 4 of length 3 (-)** Agribusiness Diversified agroproduction Photovoltaic energy Land use conflict **Loop Number 5 of length 3 (+)** Agribusiness Diversified agroproduction Photovoltaic energy Knowledge management **Loop Number 6 of length 3 (-)** Agribusiness Diversified agroproduction Photovoltaic energy Overexploitation of aquifers

Source: Authors

3.6. The R4 y R5 group of loops of the *Dynamizing* and *Photovoltaic conflicts* constructs.

The R4 group of loops or Dynamizing loop comprises the elements related to public policies and knowledge management, and innovation in the relationship between photovoltaic energy and agribusiness. The Dynamizing loop is defined as those factors that can speed up or slow down the positive interaction between photovoltaic energy and agribusiness. Public policies are the set of governmental, legislative, or judicial measures that can help accelerate or try to stop the process of implementing photovoltaic systems in agricultural production units. At a global level, this process is favored by the Sustainable Development Goals and the Paris Agreement on Climate Change (IRENA-FAO, 2021).

Among the public policy measures that could accelerate the growth of photovoltaic energy in agribusiness are: regulating the installation of bidirectional electricity meters, developing local energy markets where photovoltaic energy purchase-sale transactions can be carried out, designing fiscal policies related to taxes for the manufacture, import, installation, operation and maintenance of photovoltaic systems, whether for self-consumption purposes or sale to the electricity system. Additionally, it is necessary to regulate the performance of traditional energy providers with the new actors on an equal footing of conditions. On the contrary, some measures that could slow down the growth of photovoltaic energies in agribusinesses are to continue subsidizing the traditional actors of the conventional electrical system, placing higher taxes on the development of photovoltaic power, and prohibiting the sale of surplus photovoltaic energy, among others. It should be noted that different countries, regions, and municipalities are currently developing public policies based on their own political, economic, social, environmental, cultural, and technological reality.

The other element that has been selected to be part of this Dynamizing loop is that of knowledge management and innovation. It is defined as the creation, storage, dissemination, application, and protection of photovoltaic technology oriented towards agribusiness development in correspondence with the organizational learning derived from the Photovoltaic-Agribusiness interaction.

The increase in the efficiency of solar panels and the reduction in their prices is evidence of the technical-commercial advances that are taking place in the photovoltaic field. The same happens with the functionality and applications of photovoltaic inverters, solar batteries, support structures, and other components. An experience that is reaching great relevance is the possibility of solar panels sharing the same land as agricultural production through the so-called agrophotovoltaic system technology, which includes developing solar structures that allow agricultural production on the ground, while photovoltaic production occurs a few meters above. The possible positive effects of these new crop management systems are being evaluated and validated.

Conversely, the R5 group of loops of the *Photovoltaic conflicts* construct is defined as a set of possible unwanted or adverse effects generated in the Photovoltaic-Agribusiness interaction due to poor management of photovoltaic technologies and agribusiness. Specifically, in this research, reference is made to the management and final disposal of photovoltaic waste, the overexploitation of aquifers, and conflicts over land use.

The photovoltaic waste element refers to dismantling photovoltaic components once they have completed their useful life, are damaged and need to be replaced, or become obsolete and are removed from the original space where they were installed. Therefore, they should be subject to reduce, reuse, and recycle practices within the so-called circular economy framework. One possibility is to ship PV components in good condition removed from PV systems for routine maintenance, from advanced countries in this field to developing countries starting with these technologies.

The overexploitation of aquifers represents the second element of the *Photovoltaic conflicts* loop due to the possibility of agricultural producers benefiting from photovoltaic systems that supply energy at low prices. This could lead to expanding the irrigation surfaces, which must go hand in hand with the possibility of the aquifers supplying the required additional water. If they do not have this capacity, the aquifers could reduce their recharge capability and become salinized. In crop irrigation systems, when the limitation is no longer the availability and price of energy, the limitation becomes the availability of water in the aquifers. This issue could negatively affect the sustainability of agricultural production systems.

Conflicts in land use represent the last element in this loop of Photovoltaic Conflicts. These conflicts arise from the pragmatic vision of the occupation of the surface and the more aesthetic vision of transforming the agricultural landscape with the massive presence of solar panels. Crops have traditionally occupied the territory in rural areas, and this occupation is having competition from solar systems.

Proper management of these conflicts so that they do not harm agribusiness will result from sound public policies and innovative knowledge management processes.

4. Conclusions and recommendations for future studies

After analyzing the interdependence relationships between the *Agribusiness* and *Photovoltaic energy* constructs, aimed at achieving higher levels of productivity, competitiveness, and sustainability, the following conclusions have been reached:

• There is a relationship of interdependence between the *Agribusiness* and *Photovoltaic energy* constructs. If this relationship is developed correctly, it can increase agricultural production units' productivity, competitiveness, and sustainability. This improvement is shown in the positive feedback loops between the *Photovoltaic Energy, Diversified*

Agroproduction, and *Agribusiness* constructs as presented in the causal diagram that constitutes an original contribution of this article (Figure 1).

• The characteristics of the electrical service received by the agricultural production unit and the motivations of its owners are the two critical factors for the agroproducer to decide to install or not a photovoltaic generation plant in the production unit. A classification of the current situation of the electricity supply and the expected situation was designed in this research. It represents an original contribution that typifies the current state and the expected state.

• The agricultural production units that install a photovoltaic system will most likely achieve a better development performance in their production and agribusiness processes than those that do not have one, generating a gap between both situations, which allows visualizing the problem under study.

• Diversified agroproduction is essential to understanding and integrating the interdependent relationships between photovoltaic power and agribusiness. Without agroproduction, there is no agribusiness. Neither would photovoltaic energy systems be necessary if there were no production processes that require electricity as a fundamental input for agricultural production.

• Favorable public policies and knowledge management constitute two positive feedback loops that can speed up the integration processes of photovoltaic energy with agribusiness through diversified agroproduction.

• Inadequate final disposal of photovoltaic waste, conflicts over land use, and overexploitation of aquifers for irrigation purposes represent three negative feedback loops. These elements could harm the future progress of the interrelationships between photovoltaic energy and agribusiness.

The following recommendations are made:

• Carry out empirical studies in agricultural production units that verify and prove that the installation of photovoltaic plants can be a determining factor for better agribusiness performance or if, on the contrary, it is a spurious variable. In any case, it must be estimated what the effect could be.

• Design and validate a diagram of flows and levels between the constructs and elements under study. These activities represent the second phase of this research based on the System Dynamics methodology.

• Delve into the theoretical and empirical study of the direct and inverse relationships in the causal model of interrelationships between the *Photovoltaic Energy* and *Agribusiness* constructs.

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