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S4 Framework for the Integration of Solar Energy Systems in Small and Medium-Sized Manufacturing Companies in Mexico

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Abstract: Currently, the industrial sector consumes more than 60% of the energy produced in Mexico, mainly from fossil fuels, causing negative impacts on the environment and human beings. Solar energy helps companies diversify their energy sources, generate savings, and reduce dependence on fossil fuels. Moreover, the environmental impact can be reduced when CO_2 emissions are reduced. Nevertheless, in Mexico, less than 3.5% of the electricity comes from solar energy, and along with a lack of information about the technical and social aspects involved in photovoltaic (PV) systems, it is difficult for companies to analyze and evaluate relevant data, and thus make effective decisions based on their needs. As such, companies cannot understand the complete lifecycle of PV systems, and, usually, the economic, environmental, and technical decisions are made only using the installation analysis, which is only one stage in the lifespan of PV systems. This paper proposes an S4 framework with the sensing, smart, sustainable, and social features that small and medium-sized companies must consider to install, operate, and dispose of PV systems, considering the Mexican context. The current literature does not show a complete classification to cover the essential S4 features to describe PV systems, so companies only have partial information when deciding about the installation of PV systems. This framework considers all the needs that may exist during the PV systems' lifecycle, making a detailed evaluation of each of its elements in each lifecycle stage. Consequently, this S4 framework gives a complete guideline allowing companies to decide on PV systems. Finally, this paper presents a case study about a Mexican company that uses the proposed S4 framework to analyze the PV's lifespan.

Keywords: renewable energy; solar energy; photovoltaic system; photovoltaic panel

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Citation: Pérez, C.; Ponce, P.; Meier, A.; Dorantes, L.; Sandoval, J.O.; Palma, J.; Molina, A. S4 Framework for the Integration of Solar Energy Systems in Small and Medium-Sized Manufacturing Companies in Mexico. *Energies* **2022**, *15*, 6882. https://doi.org/10.3390/en15196882

Academic Editor: Marco Pasetti

Received: 10 August 2022
Accepted: 8 September 2022
Published: 20 September 2022

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1. Introduction

The use of energy plays a crucial role in the economic development and welfare of a nation [1]; currently, the world economy depends heavily on fossil fuels to satisfy the energy demand, which is the primary source of greenhouse gas (GHG) emissions [2], and thus climate change and global warming. Because of the negative environmental impacts of fossil fuels and their depletion, the global search for sustainable and more environmentally friendly alternative energy sources has grown in recent years [3].

Renewable energies (RES) can assist in diversifying energy carriers, improving access to clean energy sources, limiting the use of fossil fuels and saving them for particular applications, and reducing pollution [4]. In other words, renewable energy sources, such as solar, wind, hydro, and biofuels promote the transition into a less carbon-intensive and more sustainable energy ecosystem [5]. Solar energy is viable because it is a clean, renewable, and widely available energy source. However, despite its abundance, it only accounts for a small portion of the world's current energy mix, which is rapidly changing because of global efforts to improve energy access, supply security, and combat climate change [3].

The importance of energy in industrial development is crucial since a large amount of the energy produced nowadays is used in industrial processes, mainly due to the use of electricity to generate power in the technologies necessary for production [6,7]. Because of this, the industry sector (manufacturing and construction) is responsible for about 18% of the global GHG emissions, while the production of electricity and heat represents 31% of the total GHG emissions [8] (p. 2). According to ref. [9], in Mexico, electricity has almost doubled its participation in the final energy consumption of the industrial sector between 1995–2015, mainly due to the substitution of technologies, the automation of industrial processes based on electricity, and the accelerated growth of less intensive industries in thermal energy consumption.

In 2019, in Mexico, the industrial sector consumed almost 60% of the electricity produced in the country, followed by the consumption of residential, commercial, and public sectors, as shown in Figure 1a (own elaboration with data from ref. [10]). On the other hand, Figure 1b (own elaboration with data from ref. [11]) shows that almost 75% of electricity generated in Mexico comes from fossil fuels (natural gas, oil, and coal), and alternative sources produce the remainder; hydropower has the highest participation, at 8.77%.

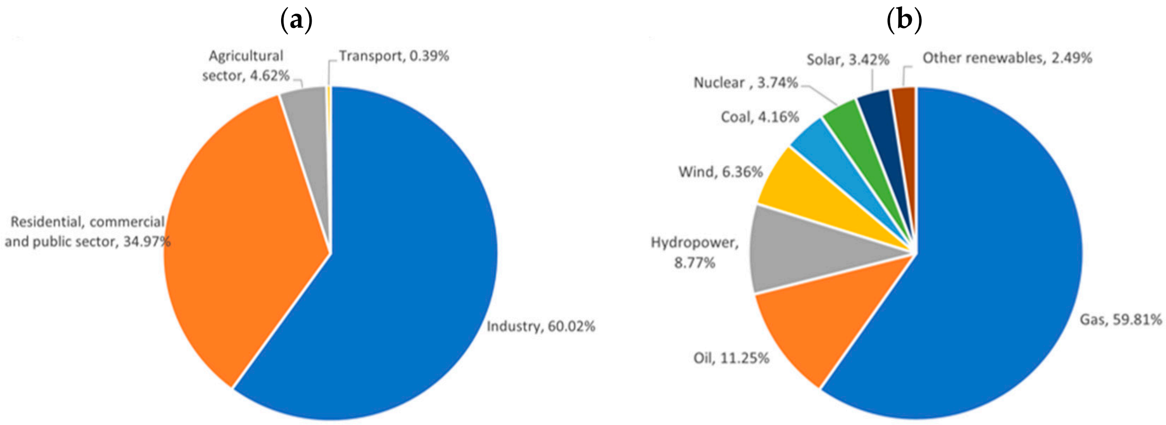

Figure 1. (**a**) Share of final electricity consumption by sector, Mexico, 2019; (**b**) share of electricity production by source, Mexico, 2020.

The Mexican government has planned to generate 35% of electricity from renewable sources by 2025 [12,13]. According to ref. [12,14], the country's alternative sources with the highest potential are wind and solar power, with an available potential of 15 GW and 11.6 GW, respectively. Nevertheless, the current installed capacity of these technologies is 0.7 GW for wind energy and 0.006 GW for photovoltaic (PV) energy [15].

Mexico has vast potential for the use of solar energy due to its high levels of irradiation (a daily average of 6.36 kWh/m^2) to the length and breadth of the country [16]. Compared to this potential, the solar PV market is still reduced; as mentioned before, the current installed capacity is only 0.006 GW, corresponding to less than 3.5% of the country's electricity production (Figure 1b). However, in recent years, there has been an exponential growth in the installation of new solar PV plants, both large-scale and solar distributed generation, as well as a growth in research and investment for its development.

Businesses and industries use solar technologies, especially PV panels, to diversify their energy sources, improve efficiency, and save money. On the other hand, government incentives derived from the 2013 Energy Reform, combined with the recent decrease in solar equipment prices, the quick payback, and the long-term savings, make the investment in solar power a good financial decision for businesses. Regardless, in Mexico, there is a lack of information, and the technical and social aspects involved in PV system installations are often unknown, which does not allow companies to analyze and evaluate relevant data to make effective decisions based on their needs regarding PV solar energy systems.

State-of-the-Art Review

Several research papers consider laws and regulations, sustainable aspects, and meteorological variables, among other technical and social aspects. Nevertheless, these papers mainly focus on particular aspects of PV systems, and they do not present a complete framework that can be used as a reference to understand each stage in the lifecycle of PV systems. Moreover, the current research studies generally cover countries in Europe, Asia, and North America, and there are very few papers about Latin American countries. In addition, these studies do not integrate technical and social aspects, considering the lifecycle of the PV system; hence, the importance of developing a framework that contains all the relevant data and information that Mexican companies need to consider when installing PV systems. Table 1 shows a comparison between the existing frameworks and this proposed framework.

Table 1. Comparison between existing frameworks for the integration of solar energy systems and this proposed framework.

Name	Author(s)	Year	Location/Country	Focus
S4 framework for the integration of solar energy systems in small and medium-sized manufacturing companies in Mexico	This research	2022	Mexico	A framework that contains the sensing, smart, sustainable, and social features that small and medium-sized companies can consider when installing, operating, and disposing of photovoltaic (PV) systems in Mexico.
Worldwide geographical mapping and optimization of standalone and grid-connected hybrid renewable system techno-economic performance across Köppen-Geiger climates [17]	Mazzeo, D., et al.	2020	Worldwide	Worldwide techno-economic mapping and optimization of standalone and grid-connected PV–wind hybrid renewable energy systems to supply the electrical demand of an office building district.
Solar energy potential assessment: A framework to integrate geographic, technological, and economic indices for a potential analysis [18]	Zhang, Y., et al.	2020	China	Estimation of China's solar energy potential considering geography, technology, and economic factors.
A conceptual framework on the integration of solar energy systems in heritage sites and buildings [19]	Lucchi, E., et al.	2020	European Union and USA	Review of the available literature on integrating Renewable Energy Systems (RES) in heritage sites and buildings.
Photovoltaic solar energy: Conceptual framework [20]	Sampaio, P., Gonzalez, M.	2017	Worldwide, mainly the USA, China, and Germany	Systematic literature research for the following themes: ways of obtaining energy, its advantages and disadvantages, applications, current market, and costs and technologies.
A study of existing solar power policy framework in India for viability of the solar projects perspective [21]	Rohankar, N., et al.	2016	India	Review and summary of various schemes under the policy framework regarding the viability of the solar power projects in India.

Table 1. *Cont.*

Name	Author(s)	Year	Location/Country	Focus
Optimal energy mix for transitioning from fossil fuels to renewable energy sources–the case of the Mexican electricity system [22]	Vidal-Amaro, J., et al.	2015	Mexico	Methodology to determine the optimal mix of RES and fossil fuels in the Mexican electricity system by considering the hourly values of RES production and electricity demand.
Building a better solar energy framework [23]	Weismantle, K.	2014	Europe and USA	Review of European and USA solar frameworks with examples of implementations in different localities.

This paper is based on S4 features used to design and create novel products and services in different areas, as presented in Ref. [24]. This paper takes advantage of S4 features and presents a complete framework for evaluating and installing PV systems in Mexican manufacturing companies. In addition, the approaches of S3 (Sensing, Smart, and Sustainable) and S4 (Sensing, Smart, Sustainable, and Social) have emerged as a response to the reconceptualization and redesign of processes that companies have begun to make through new practices and operational strategies, including the use of new technologies. These approaches have improved the design of products and services, as mentioned by Ref [24]. S3 products, processes, manufacturing systems, and enterprises provide added value by incorporating specific characteristics and functions, which becomes a strategy for remaining competitive in the marketplace by offering solutions to contemporary social problems and responding to changing consumer demands.

In the research work presented in Ref. [25], the implementation of the S3 framework for redesigning a computer numerical control reconfigurable micro-machine tool is presented, and it is concluded that the framework is a coherent and valuable set of guidelines for offering a new generation of products since an improvement between the two products was verified. The reference framework proposed by Ref. [26] integrates different models intending to help enterprises to deal with current concerns, such as the product, process, manufacturing system, and the strategic use of information and communication technologies, sustainably and smartly using sensing capabilities. Ponce (Ref. [27]) used the S3 product reference framework and the integrated product, process, and manufacturing-system development reference model [28] to show how social communication between consumers and products can be classified and how it can be used in a new product development process using as a case study a smart social thermostat. In addition, Ref. [29] described how S3 technologies for the agri-food sector could be developed using a systematic process for new product development, and how it can respond to current challenges of agri-food industries, presented as case studies and as an intelligent greenhouse, a sun tracker trajectory, a hexapod robot for field monitoring, and an agricultural drone. Finally, Ref. [30] designed a low-cost robot, Robocov, to respond to the COVID-19 pandemic by implementing artificial intelligence and the S4 concept for the design. As a result, developing and assessing a S4 framework regarding PV systems provides a more effective solution than conventional ones.

This work proposes an S4 framework to inform small or medium-sized companies about the sensing, smart, sustainable, and social features they must consider to install, operate, and dispose of PV systems in Mexico. This framework considers all the needs that may exist during the life cycle of a PV system, in addition to making a more detailed, and therefore a more valuable, framework as it considers the technical and economic feasibility of the project.

This paper is structured as follows: Section 2 presents the steps to use the S4 framework, as well as a detailed description of the elements that make up each of the categories and the stages in which they are used; Section 3 presents a case study with a Mexican company located in Baja California, Mexico, where the S4 framework is applied to complement a PV project proposal for its production plant roof; Section 4 shows a discussion of the elements chosen for the case study; and finally, the conclusions are in Section 5.

2. Materials and Methods

This section presents the proposed methodology for the S4 framework. It starts by describing the framework and its primary functions. Then, its flowchart is presented and described. Finally, there is a description of the features that make up each of the S4, and the stage of the lifecycle in which they are used is also mentioned.

The S4 framework puts together the sensing, smart, sustainable, and social features involved in PV systems, focused on the Mexican context. The main function of the framework is that small and medium-sized companies can analyze each feature and its role in each stage of the PV system and, thus, choose the features that best meet their needs. According to its function, each feature has been assigned to an "S" (see Table 2), which makes the analysis more manageable and allows the integration of the features in all the stages of the system's lifecycle.

Table 2. Description of the S4 framework.

"S"	Description
Sensing	Sensors needed to install, operate, and dispose of a photovoltaic (PV) system; sensors for measuring meteorological and power variables and for maintenance and monitoring purposes.
Smart	Features that use data/information and automated reasoning for decision-making.
Sustainable	Environmental impact analysis of the PV system components from manufacturing to disposal.
Social	Legal and regulatory framework to install, operate, and dispose of a PV system in Mexico; economic viability analysis; and analysis of population acceptance.

Figure 2 presents the summarized conceptual S4 framework. As observed, the framework considers all the elements involved in PV systems: meteorological variables such as the sun, PV panels, inverters, energy management systems, and smart meters. Additionally, it considers which type of system is more feasible regarding the needs of the company: standalone or grid-connected; energy storage technologies are contemplated for standalone systems. The sensing, smart, sustainable, and social features are presented in each stage of the system: in the evaluation/diagnosis to analyze the feasibility, in the installation to verify a proper mounting, in the operation to monitor correct functioning, and in the disposal to guarantee correct waste management. At the disposal stage, a reuse sub-stage is added in case some elements have not yet completed their lifecycle and can be reused for another PV system.

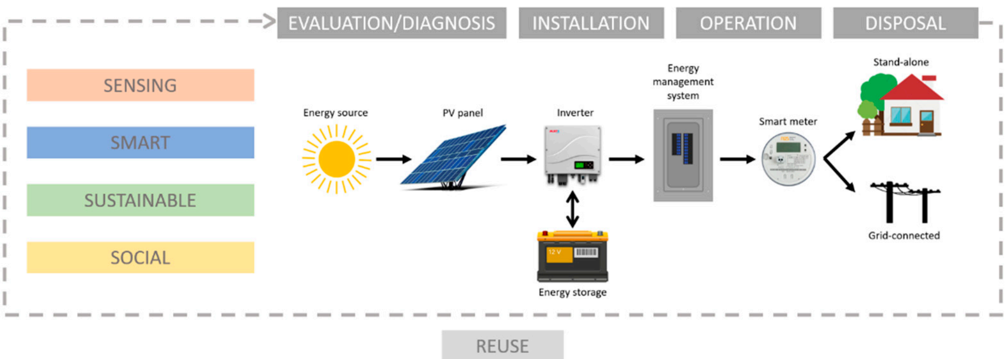

Figure 2. Summarized conceptual S4 framework to install, operate, and dispose of a PV system.

As each stage and S4 feature are connected, there may be features used in all the stages or even just in one; the following paragraphs will describe the stage(s) in which each feature is implemented.

Figure 3 shows the flowchart of the proposed S4 framework. The description of this flowchart is as follows:

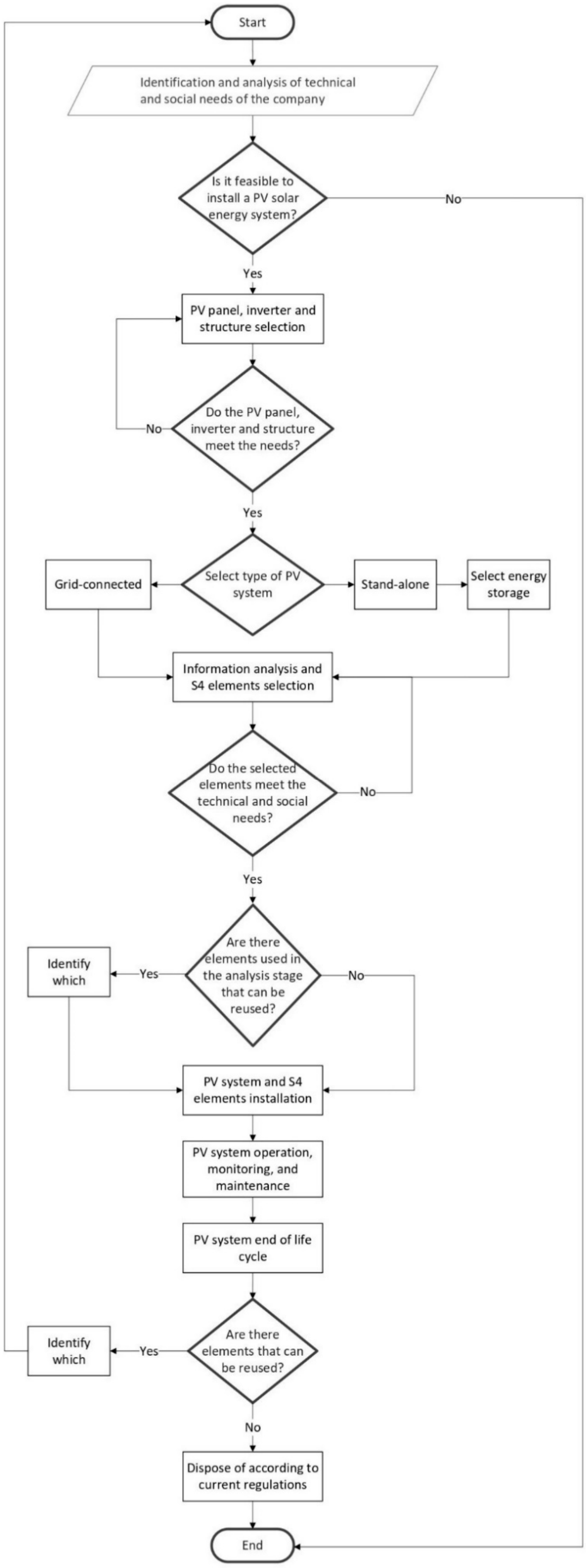

Figure 3. Flowchart for the S4 framework to install, operate, and dispose of a PV system.

Step 1: Identify the company's technical and social needs.

- Technical needs: energy consumption, available area to install the PV system, and solar radiation received.
- Social needs: investment considering governmental incentives and governmental restrictions.

Step 2: Based on the technical and social needs analysis, determine if installing the PV system is feasible.

Step 3: If it is feasible to install the system, select the PV panel, inverter, and structure that best accomplish the company's needs, considering: cost, power supplied, space, guarantee, and maintenance.

Generally, solar panels are classified into three categories based on the material used for their construction:

- Monocrystalline silicon panels: their cells are made of a single silicon crystal. They are usually the most expensive because they are the most difficult to manufacture, but tend to last longer and have higher efficiencies. Monocrystalline cells appear black and uniform in finish [31,32].
- Polycrystalline silicon panels: their cells are made up of several silicon crystals, they are cheaper and easier to manufacture than monocrystalline, but they are less efficient. A blue finish, rectangular shape, and speckles are identifiers of polycrystalline cells [31,32].
- Thin-film solar panels: they are thin, flexible, and manufactured from layers of semiconducting materials, such as silicon, cadmium telluride, and copper indium gallium selenide. They have low efficiencies and tend to degrade more quickly than crystalline panels [31,32].

On the other hand, inverters can be classified into three different types based on their size, mode of operation, and configuration topology:

- Central inverter: Before the strings of the PV array are connected to the energy management system, all of them are connected to the DC side of a central inverter, and the single AC output of this inverter is connected to the energy management system. The central inverter is the most traditional topology because it implies an easy system design and implementation, low costs, and easy accessibility for maintenance [33]. Monitoring using only a few central inverters is more accessible than multiple string or micro-inverters, and involves less energy consumption [34,35].
- String inverter: Each PV string is connected to a DC side of an inverter, and all AC outputs of string inverters are combined and connected to the energy management system. In other words, as the name indicates, each string of PV modules has its own inverter. This type of inverter is smaller than central inverters and allows a better maximum power point tracker per string [33].
- Micro inverter: Also known as a module inverter because each module has one inverter connected to its back. The panel DC terminals are connected to the inverter DC side, and all inverters AC wires are combined and connected to the energy management system. Micro inverters have bigger resilience to partial shading effects and allow better monitoring of the module, but they are also more expensive and have a higher maintenance cost [33,35].
- The development of smart inverters has been growing in recent years; its description and operation can be seen in detail in the smart elements section.
- PV panel mounting structures play a vital role in solar power systems since they help panels to rest and be stable, preventing them from damage. The mounting structure allows PV panels to be located at a precise tilt angle to receive maximum sun radiation, so it is essential to look for structures with materials that are highly durable, rust-free, and corrosion-resistant [36]. Thus, many structure solutions have been developed to meet different PV system's needs:
- Ground mount: It allows the installation of multiple rows of panels on the ground, allowing a safe installation and easy access for maintenance [37]. The main disad-

vantage is the exposure to vandalism and accumulation of dirt, leaves, and snow; therefore, it is only recommended for secure locations [36,38].

- Pole mount: It is used for anchoring panels to poles. It is common in public areas where the system is space constrained [37]. There are two types of pole mounts, top-of-pole, which elevates the module several feet off the ground and allows it to sit on the top of a pole, and side-of-pole, which anchors the PV module to the side of poles [36,38].
- Roof mount: There are roof mounts with and without roof penetration; both allow the use of unused spaces. A roof mount with penetration installs the PV system parallel to the roof, but it has many disadvantages; for example, the penetrations can cause roof leakages, and the roof orientation and angle might not be optimal, which can cause a waste of potential energy [36,37]. A structure without roof penetration has low material costs, and it is optimal when the roof is flat, but it may require structural engineering and/or roof reinforcement because of added weight [37,38].

Step 4: Select the type of PV system: standalone or grid-connected. Standalone PV systems operate independently of the grid and require a storage system, usually a battery, to store the electricity; they are usually used to power buildings in isolated areas or that are not connected to the grid. On the other hand, grid-connected systems do not require batteries, and if the system generates more electricity than required, the excess can be sold to the grid [39].

Different technology options exist for energy storage used for PV systems. Before choosing one of these technologies, it is crucial to analyze which of these options is the one that best meets the company's needs, considering: location, the amount of energy produced by the PV system, the availability of technology, and budget:

- Hydrogen: The electricity generated by the PV system is used to electrolyze water; then, the hydrogen gas is collected and can be used as a fuel. The H_2/O_2 fuel cell is a highly efficient device for converting hydrogen back to electricity, and it has zero carbon footprint during this process [40].
- Compressed air: The electrical energy produced by the system is used to run compressors to compress air and store it in underground, above ground, or underwater containers; then, the air is decompressed and used to generate electricity by supplying a turbine. Although this technology is not yet widely implemented, it promises high efficiency [40,41]. Since it is an immature technology and the stored energy could be used for low power demand, it is not recommended for use in companies until it is demonstrated that the efficiency and the power storage are good enough for industrial applications in the manufacturing process.
- Battery: This is the most used storage technology. There are different types of battery technologies:
    - Lead-acid batteries: The cheapest energy storage option, reliable, and can be easily disposed of and recycled. This battery requires regular maintenance and has a short lifespan, between 5–10 years [42,43]. Even though this technology is outdated, it could be a feasible option for the Mexican context since economical factors could be important for medium or small-size companies. Thus, the companies could consider a better storage option if the economic inversion allows the selection of a more expensive system.
    - Lithium-ion batteries: They have a high battery energy density, which means they can store more energy in a smaller space, require no regular maintenance, and have a longer lifespan (10 years); however, they are also more expensive and have a higher chance of catching fire [42,43].
    - Nickel-cadmium batteries: Used for commercial-scale projects because they are durable, can operate at extreme temperatures, do not require a complex battery management system, and are maintenance-free. Nevertheless, cadmium is highly toxic and is banned in some countries, which makes this type of battery challenging to dispose of [42,43].

- ○ Flow batteries: An emerging technology that has the most extended lifespan (30 years). They are low-maintenance but are more expensive and have a low storage capacity compared to other storage technologies [42,43].

Step 5: Analyze the collected information and select the sensing, smart, sustainable, and social features that best meet the technical and social needs.

Step 6: Identify if there are elements used in the analysis stage that can be reused in other stages. For example, some sensors used to measure meteorological variables (irradiance, wind speed, direction, humidity, etc.) can be used in other stages of the system.

In this stage, it is possible to create a morphological matrix that allows several solutions to be found according to the company's needs. These solutions can be explored and assessed, as presented in Refs. [44,45]. Each function and sub-function in the morphological matrix is evaluated according to the principal function. Since the main elements regarding social, sustainable, smart, and sensing features are considered, it is possible to evaluate each solution obtained from the morphological matrix comprehensively and holistically. It is not easy to achieve this kind of integral evaluation when only a conventional evaluation is conducted.

Figure 4 illustrates the morphological matrix applied in PV systems. The principal function is evaluating/installing a PV system considering its four stages (see Figure 2). The sub-functions are the sustainable, social, smart, and sensing features, and the elements integrated into these sub-functions are the items of each feature (see Table 3). A specific trajectory is described when specific items from each feature are selected. Thus, each trajectory represented in Figure 4 shows a particular solution that could be evaluated and compared against additional solutions, so the solution that best meets the company's requirements is adopted. In addition, Figure 5 shows some sensors that are used in other stages of the PV system lifetime.

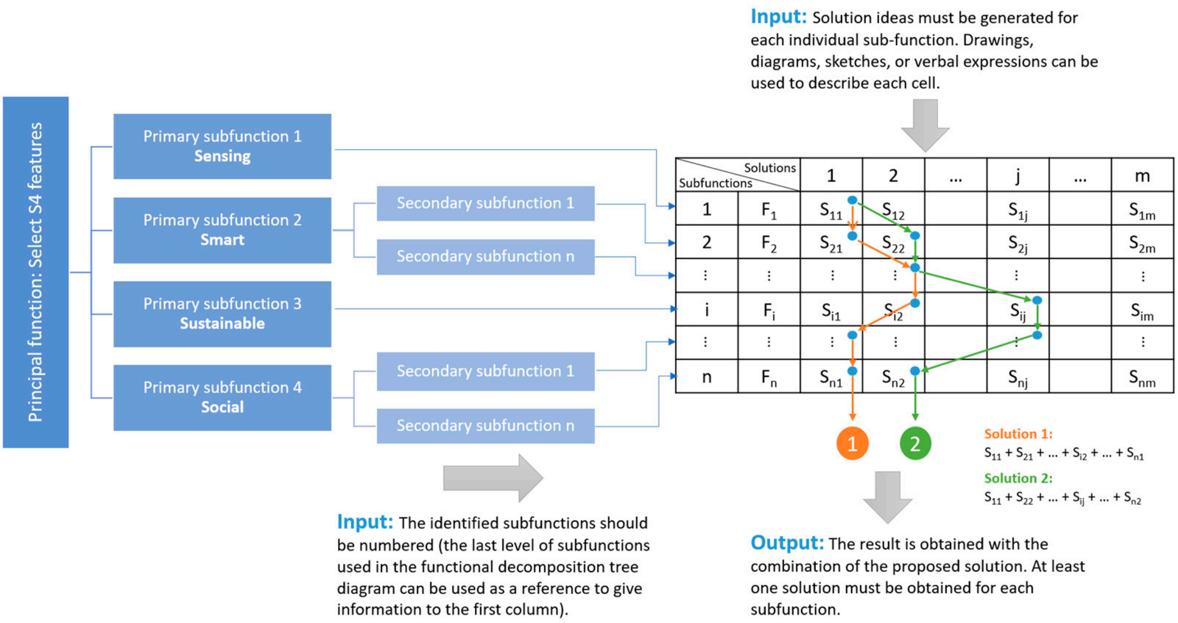

Figure 4. Morphological matrix for the S4 framework in PV systems.

Step 7: Install the PV system and the S4 elements chosen.

Step 8: PV system's operation and maintenance (O&M); this step also includes monitoring through the S4 elements.

A PV system with no regular maintenance becomes fatigued over time, which may cause faulty scenarios and provoke the system to deteriorate over time and become less productive, in addition to causing other deficiencies such as burning, electrocution, and other electrical faults and perturbations [46].

Table 3. S4 framework elements.

Sensing	Smart	Sustainable	Social
1. Panel surface temperature sensor 2. Solar radiation sensor 3. Voltage sensor 4. Current sensor 5. Air/ambient temperature sensor 6. Battery voltage sensor 7. Tilt angle sensor 8. Wind speed sensor 9. Wind direction sensor 10. Humidity sensor 11. Dust sensor 12. Rain/precipitation sensor 13. Load current sensor 14. Converter temperature sensor 15. Photovoltaic station weather system 16. Remote sensing and GIS 17. WSN node	1. Advanced metering infrastructure (AMI)–smart meter 2. Solar tracking system 3. Digital twins 4. Data storage 5. Data analytics 6. Predictive analysis 7. Monitoring system 8. Battery management system 9. Intelligent modeling techniques for forecasting solar energy 10. Smart inverter	1. Solar panels' total CO_2 emissions 2. Inverters' total CO_2 emissions 3. Land use 4. Water use and consumption 5. Noise and visual disturbances 6. Impact on flora and fauna of the installation place 7. Waste management	1. Legal and Regulatory Framework a. General Law of Ecological Balance and Environmental Protection b. General Law of Sustainable Forest Development c. General Law of Human Settlements d. Regulations e. NOM-001-SEDE-2012 f. Regarding hazardous, urban, and special management waste g. NOM-059-SEMARNAT-2010 h. NOM-138-SEMARNAT-2005 i. NOM-041-SEMARNAT-1993 j. NOM-081-SEMARNAT-1994 k. NMX-ANCE: Standards of the Association for Standardization and Certification l. 2013 Energetic Reform 2. Economic parameters a. Government incentives and special loans b. Investment c. Return on investment d. Savings 3. Population acceptance

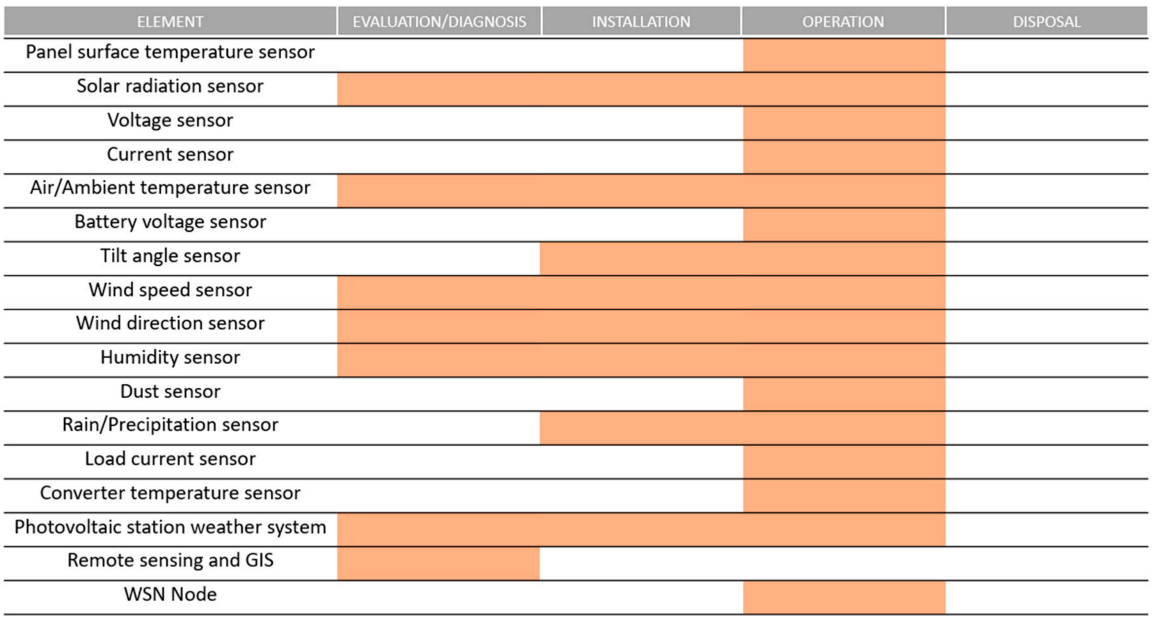

Figure 5. Sensing elements through the PV system stages.

A correct O&M allows for increased efficiency and energy delivered, decreased downtime, extended system lifetime, reduced cost of O&M, safety, risk reduction, and an enhanced appearance and image [47].

The maintenance of a PV system can be divided into four categories:

- Corrective maintenance: Activities performed to restore a system malfunctioning or blackout due to an event resulting from a system fault occurring at different levels of the network. It includes fixing, repairing, replacing, and other correction tasks to avoid significant equipment damage. Methods and techniques related to corrective maintenance are artificial intelligence, panel water and dry cleaning, snow removal, equipment technical maintenance, and shading mitigation techniques [46].

- Urgent case maintenance is mandatory after a significant force event in the system because it makes corrections in a hurry, prioritizing the prevention of more extensive damages. The approach is similar to the corrective one, but includes critical risk decision-making. Thus, it is crucial to identify the affected criteria (PV system or personnel), the risks (damage to PV system or health hazards), and the initial cause [46].
- Predictive maintenance: It mathematically evaluates the system's condition by performing scheduled/continuous real-time monitoring, and hence, it predicts the optimal time to perform maintenance and reduce hazardous effects that may happen in the future. The different techniques used in predictive maintenance are the failure mode and effect analysis (FMEA) approach based on real data, artificial neural network (ANN)-based models, the multivariate linear regression model (MLR), and the smart maintenance decision support system (SMDSS) [46].
- Preventive maintenance: Used to perform maintenance on a pre-scheduled time interval regardless of the system's condition to decrease and prevent bigger damages that might occur in the future. Some preventive maintenance strategies are cooling PV panels, transformer-less inverters, lightning protection, and computation inverse design [46].

Step 9: End of the PV system's life cycle. Evaluate if there are elements that can be reused in a reinstallation or recycled; if not, dispose of them according to current regulations. This framework focuses on a circular economy applied to PV systems; that is why the opportunities for value creation are highlighted in each stage of the PV system value chain, including the end-of-life stage, which is described in detail in the sustainable section.

The elements that make up each of the S4 can be observed in Table 3, and below there is a more detailed description of each.

2.1. Sensing

This category's elements help acquire relevant data and information in real-time for decision-making, which can also help carry out predictions [24]. In this category, the sensors needed to install, operate, and dispose of a photovoltaic system are found. Some of these sensors measure meteorological variables, others measure power, and others can be used for system maintenance.

1. **Panel surface temperature sensor**: Measures the PV panel's degree of hotness or coolness. There are two main types of PV module temperature sensors: surface contact sensors, such as back-of-module sensors, which are attached directly to a surface and measure the temperature via physical contact. The other type are infrared temperature sensors, which are non-contact and measure the surface temperature by sensing the infrared radiation given off by the object; these are appropriate when temperatures are extremely high [48]. Panel surface temperature measurements are essential for assessing PV system performance because it estimates the temperature at the semiconductor junction inside the panel. This temperature, combined with other electrical and atmospheric data, can predict the solar system's expected power output [49].
2. **Solar radiation sensor**: The most common instruments for measuring this variable are: pyrheliometers for measuring the direct beam radiation, pyranometers for measuring the combined direct beam and the diffuse radiation on a horizontal surface, and pyranometers with an additional shaded ring for measuring the diffuse radiation on a horizontal surface [50]. This variable's measurement helps predict the system's expected power output.

3. **Voltage sensor**: Used to measure the voltage generated by the solar panel [51] and, thus, by the system. Each component of the PV system needs to be monitored to detect the current and voltage and to evaluate its efficiency and security [52].
4. **Current sensor**: Current sensors are needed in PV systems for measuring the current generated by the solar panel, controlling the converters and inverters, optimizing the power extraction from the panels, and fault detection for safety [51,53]. When multiple PV modules are connected in parallel to the inverter, by detecting the operating current of each PV group, the user can effectively monitor the working state of the panel and obtain the maximum power point (MPP) of the system, and thus, improve its efficiency [52].
5. **Air/ambient temperature sensor**: Measures the temperature of the environment, evaluating maximum and minimum temperatures in a specific period of time [54]. Ambient temperature affects the performance of a PV system because solar cells are susceptible to temperature [55]. Hence, the importance of measuring this variable with the appropriate sensor.
6. **Battery voltage sensor**: Its primary function is to prevent batteries from being damaged due to over-charging and to cut off the current from the PV array when the battery voltage reaches a minimum level, reducing battery performance or lifespan [56].
7. **Tilt angle sensor**: Commonly used for solar tracking because it detects the panel's angular position in real-time to guarantee the sunlight is always as vertical as possible to the module and, thus, obtain the most significant amount of radiation possible, improving the output of solar energy systems. Tilt sensors are compact, affordable, and easy to install and use [57,58].
8. **Wind speed sensor**: The instrument used to measure the air velocity is called an anemometer. There are different types of anemometers, such as a cup anemometer and a vane anemometer; the first one is the most used in meteorological stations [59]. Wind monitoring is vital because significant wind loads can reduce the module's stability [60].
9. **Wind direction sensor**: Instrument used to measure horizontal wind direction. A low-inertia wind vane is used to sense this variable. When the wind direction changes, the tail wing rotates to drive the axle magnet to rotate through the shaft, obtaining accurate wind direction information [61].
10. **Humidity sensor**: It detects and measures water vapor in the atmosphere. Humidity sensors can be divided into relative humidity and absolute humidity [62]. Measuring this variable is important because high levels adversely affect solar radiation and reduce cell performance and efficiency [63].
11. **Dust sensor**: Used to detect and monitor the amount of dust on the surface of the PV modules, which enables the time when modules should be cared for and maintained through cleaning to be ascertained. The modules' cleaning helps achieve maximum power output as the PV cell's surface area becomes fully exposed to solar radiation [64].
12. **Rain/precipitation sensor**: Rain sensors are used to record the accumulated precipitation at a location for a given time. The tipping bucket rain gauge is the most used instrument for measuring rainfall, and it operates on an internal tipping mechanism that tips back and forth each time a pre-set amount of rain is collected in the unit. Then, each tip is recorded by a data logger [65].
13. **Load current sensor**: As with measuring the solar panel's temperature, surface contact or infrared temperature sensors can be used to measure load current.
14. **Converter temperature sensor**: As with measuring the solar panel's temperature, surface contact or infrared temperature sensors can be used to measure the converter temperature.
15. **Photovoltaic station weather system**: An automated weather station precisely designed for solar resource assessment and monitoring of solar farm power [66]. It

measures global, horizontal, plane of the array, background irradiance; wind speed and direction; ambient temperature, and relative humidity.

16. **Remote sensing and Geographical Information System (GIS)**: Remote sensing data processed through spatial analytical software, such as a Geographical Information System, can help to determine the optimal site for solar system installation at both the micro- and macro-scales [67]. Nevertheless, the data obtained through software can often be inaccurate since the monitoring devices are not directly in the installation place. Thus, it is recommended to have accurate monitoring, which can be obtained using the sensors mentioned above.
17. **Wireless sensor network (WSN) node**: A WSN node fed by a solar PV energy harvesting system is equipped with power management devices able to supply power intelligently; it also allows the monitoring of variables of interest related to storage goods [68].

Figure 5 shows the stages in which each sensing element can be used.

2.2. Smart

Smart elements are based on intelligent systems using artificial intelligence techniques, which implies using data/information and automated reasoning for decision-making [24].

1. **Advanced metering infrastructure (AMI)–smart meter**: Allows real-time communication between the consumer and utilities about: time of use, real-time pricing, critical peak pricing, and home area networking [69]. Thus, utilities can inform the consumer about their energy consumption and budget daily; this means receiving instant feedback, which can be a powerful tool for energy conservation and management [70].
2. **Solar tracking system**: This system aligns the face of the solar panel or reflective surfaces with the sun as it moves across the sky from sunrise to sunset [71,72].
3. **Digital twins**: A digital twin is a digital replica of an object or physical system in real-time, constantly evolving through a connection to the physical system [73]. The use of digital twins in energy systems increases the possibilities in design, forecasting, and management [74]. It also allows predictions about the system to be made.
4. **Data storage**: A proper data storage system can be helpful for model prediction and decision-making. This data includes energy consumption, data on meteorological variables, and energy generated by the PV system.
5. **Data analytics**: Used to analyze data from sensor systems and, thus, improve the decision-making process at different system levels [24].
6. **Predictive analysis**: Smart modules are capable of processing a large amount of information and generating decisions based on historical data and predictive analysis; these smart modules can be autonomous and recognize and execute routines for different scenarios, as well as make decisions and execute actions to improve the efficiency of the system [24].
7. **Monitoring system**: The primary function is to monitor and gather data on the performance of the PV system in real-time [75]. A wide variety of monitoring system technologies have been proposed, such as the "Wireless ZigBee system for performance monitoring of photovoltaic panels" [76], "Data monitoring system for solar panels with Bluetooth" [77], "Monitoring system for the solar panel using smartphone-based on microcontroller" [78], "Time-series energy prediction using Hidden Markov Model for smart solar system" [79], "IoT application for real-time monitoring of solar home systems based on Arduino with 3G connectivity" [80], "Experiment-based supervised learning approach toward condition monitoring of PV array mismatch" [81], and "Low-cost datalogger intended for remote monitoring of solar photovoltaic standalone systems based on Arduino" [82].
8. **Battery management system**: Controls the charging and discharging of batteries from a PV system; it also calculates the battery state of charge (SOC) to determine its available capacity, and, thus, implement intelligent strategies to increase the battery life and thereby reduce the costs of the system [83].

9. **Intelligent modeling techniques for forecasting solar energy**: Fuzzy-based models, such as fuzzy logic, artificial neural network (ANN), and the adaptive-neural-fuzzy inference system (ANFIS), can be used for forecasting global solar energy based on sky conditions and other meteorological parameters. The results can help provide appropriate control for PV system integration, optimization, real-time power dispatch, and selecting appropriate energy storage [84].
10. **Smart inverter**: It can perform multiple functions involving reactive and real power control, such as voltage regulation, power factor control, active power controls, and frequency control, among others, in addition to its primary task of converting DC power to AC power [85]. Smart inverters also enable higher penetration levels and enhance the value of grid-tied PV and storage devices [86].

Figure 6 shows the stages in which each smart element can be used.

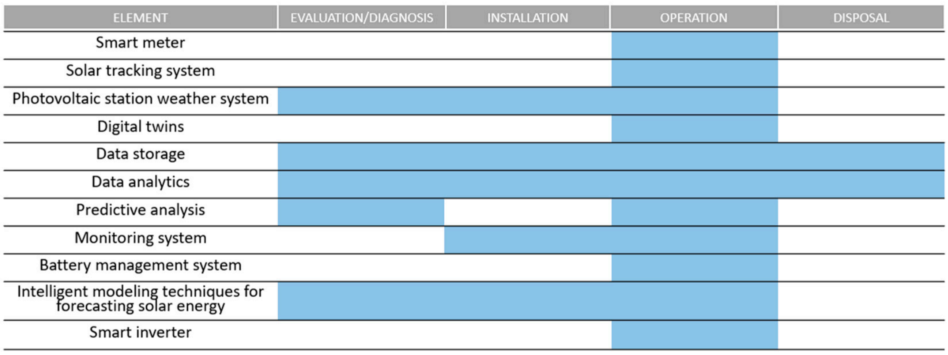

Figure 6. Smart elements through the PV system stages.

2.3. Sustainable

The sustainable category includes the impact analysis of the PV system components on the environment, from manufacturing to disposal: GHG emissions in the production and transportation, land use, noise and visual disturbances, impact on flora and fauna of the installation place, and correct disposal once the components finish their life cycle (waste management).

1. **Solar panels' total CO_2 emissions**: Includes the kilograms of CO_2 emitted for each m^2 of solar modules produced and for each kilogram of modules transported. The place of origin, the place of destination, and the type of transport used are considered. The measurement unit for this parameter is $kgCO_2$.
2. **Inverters' total CO_2 emissions**: The sum of the CO_2 emissions for production plus the CO_2 emissions for transporting the necessary inverters for the PV system. As in the previous parameter, the place of origin, destination, and transport used are also considered. The unit of measure is $kgCO_2$.
3. **Land use**: The impact of land use on the environment depends on specific factors, such as the landscape's topography, the area of land covered by the PV system, the distance from natural areas or sensitive ecosystems, and the biodiversity [87]. The construction phase usually contributes to a significant environmental impact on the land and habitat because of the earth and transport movements [88], the use of concrete and heavy machinery, and the installation of structures [87,89]. The construction phase is also considered the most impactful phase due to deforestation, which is linked to biodiversity loss and soil erosion [88].
4. **Water use and consumption**: The water consumption of PV systems is present during their entire life cycle. The water used during manufacturing processes is present in mineral processing, extraction, purification, and chemical etching [89]. During operation, water is used mainly for cooling and cleaning of the panels [90]. Nevertheless, water consumption during manufacturing and recycling processes can be considerably higher than during operation [89].

5. **Noise and visual disturbances**: The noise of solar systems can be generated from the differences in power intensities between two PV installations [89]. During the operation, PV modules do not produce significant noise pollution because they do not contain rotation or moving parts [87]. Nevertheless, during the construction phase, noise pollution for humans and wildlife is caused by heavy machinery and vehicles operating on-site [91]. The visual impact is highly dependent on the type of scheme and the surroundings of the PV systems [87]. Depending on the degree of this impact, public opinion can strongly oppose the installation and complicate its implementation; for example, if the system is planned to be installed in a natural site with intensive biological diversity and recreational areas, public disapproval could occur [89].
6. **Impact on flora and fauna of the installation place**: Deforestation to install PV systems can contribute to vegetation and fauna loss. PV modules are related to bird mortality because of either direct collision with the PV infrastructure or contact with solar flux [88]. PV systems can also generate glare due to optical reflections, which can be a source of discomfort for the fauna and the nearby populations [92]. In addition to habitat fragmentation, utility-scale solar energy infrastructures may become linear barriers to the movement patterns of certain wildlife species [93].
7. **Waste management**: Consists mainly of following the waste management plan and guidelines for replacing and disposing of batteries, panels, and other malfunctioning equipment [88]. PV components are classified as E-waste and must be sent to specialized facilities for segregation, recycling, and adequate disposal [88]. In Figure 2, there is a "Reuse" stage; this stage is included considering that there may be some elements that can be reused if the company decides to install the photovoltaic system again once the life cycle of most of the components, mainly PV modules, is over. If this does not happen, the elements that can be recycled or reused and those that must be disposed of must be evaluated considering the applicable policies. Nowadays, reused PV modules are potentially proceeded by repairing, which is practically and economically challenging [94]. On the other hand, recycling PV modules mainly implies the mechanical separation of their major components and materials.

In the case of the PV system infrastructure, the aluminum or steel of the frames and the copper of the cables have the easy potential for recycling. Recovering small amounts of valuable, scarce, or most hazardous materials might require additional and more advanced processes [94].

Figure 7 shows the stages in which each sustainable element is required.

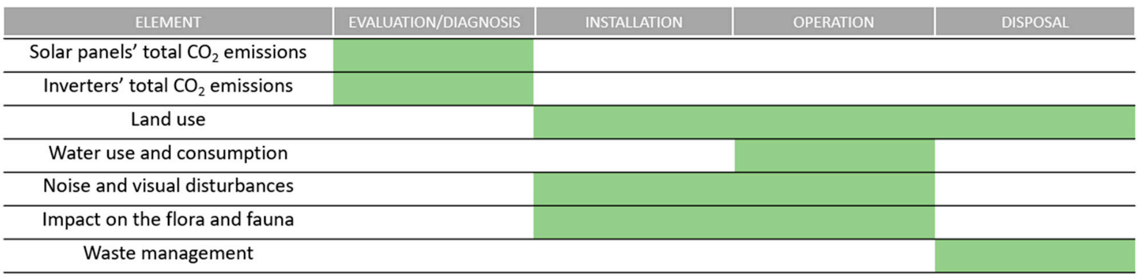

Figure 7. Sustainable elements through the PV system stages.

2.4. Social

This category is divided into three pillars. The first is the legal and regulatory framework to install, operate, and dispose of a PV system in Mexico. On the other hand, there is the economic aspect, which refers to the profitability of the system [24]. The economic aspect includes the available government incentives and their benefits, an analysis of the investment, the return on investment, and the savings generated from producing solar energy on site instead of taking it from the electricity grid. Finally, there is the acceptance of these systems by the population.

2.4.1. Legal and Regulatory Framework

1. **General Law of Ecological Balance and Environmental Protection** (LGEEPA) [95]: In this case, it constitutes the main legal instrument to assess the environmental impact of the project activity and land use change. The interference chapters include Impact Assessment Environment, Sustainable Use of Land and its Resources, Prevention and Control of Soil Pollution, and Prevention and Control of Pollution to the Atmosphere.
2. **General Law of Sustainable Forest Development** [95]: Applies in the case of clearing or requiring land use changes in forest land.
3. **General Law of Human Settlements** [95]: For authorizations, licenses, or permits for land use, construction, etc.
4. **Regulations**
    - The Energy Regulatory Commission (CRE) is the official agency of the Mexican government that grants generation permits to all users and is linked to the Energy Secretariat (SENER), which regulates all aspects of the Federal Electricity Commission (CFE) and *Petróleos Mexicanos* (PEMEX).
    - In the case of clean energy users, if solar or wind technology is used for distributed generation with a capacity of less than 0.5 MW, then it is classified as an "exempt generator" [96], which means it is not necessary to obtain generation permission. However, it must comply with CRE resolutions 2017 RES-142 and 2014 RE-119 for interconnection to the CFE network system, and comply with CFE standards for distributed generation PV systems (CFE -G100-4) [97–99].
    - Regarding the distributor/company in charge of installing the PV panel system, NOM-029-STPS standard must be complied with to ensure the safety of users, NOM-022-STPS for the safety of the facility, and NOM-017-STPS to ensure the protection of its workers [100–102] The PV modules must comply with the IEC-61730 and UL 1703 standards, mainly if the models belong to the Tier 1 category in the international market [103,104]. The inverters must comply with the protection requirements established in UL 1741 [105]. Likewise, the company or distributor must ensure the correct insulation of the system wiring, following the IEC-60364-4-41 and IEC-62548 standards [106,107].
    - LGEEPA Regulation on Environmental Impact Assessment, concerning what is established for the change of land use of forest land and the development of the project following article 5, paragraphs K and O, respectively.
    - Regulation of the LGEEPA in Matter of Prevention and Control of Pollution of the Atmosphere, which establishes the provisions and procedures necessary for controlling polluting emissions into the ambient air for the project's development in the operative part [95].
    - Regulation of the General Law for the Prevention and Comprehensive Management of Waste regarding the generation of waste in general in the different stages of the project [95].
    - Regulation of the General Law of Sustainable Forest Development, if the project considers the change of use of forest land for its development [95].
5. **NOM-001-SEDE-2012** [108]: Electrical installations generally, including those for PV systems, are governed by this standard. This aims to ensure electrical installations satisfy the safety conditions for people and the installation place in regards to electrical faults. Article 690 of this standard is dedicated exclusively to guidelines and regulations for PV systems.
6. **Regarding hazardous, urban, and special management waste** [95]:
    - NOM-052-SEMARNAT-2005 establishes the characteristics, identification procedure, classification, and lists of dangerous waste.
    - NOM-053-SEMARNAT-1993 establishes the procedures to carry out the extraction test to determine the components that make hazardous waste due to their toxicity to the environment.

- NOM-054-SEMARNAT-1993 establishes the procedures to determine the incompatibility between two or more residues considered dangerous by NOM-053-SEMARNAT-1993.
- NOM-083-SEMARNAT-2003 establishes the environmental protection specifications for site selection, design and construction, operation, monitoring, closure, and complementary works of a final disposal site for urban solid waste and special management.

7. **NOM-059-SEMARNAT-2010** [95]: Environment protection of Mexico native species, wild flora and fauna, risk categories, and specifications for their inclusion, exclusion, or change. Includes a list of species at risk.
8. **NOM-138-SEMARNAT-2005** [95]: Maximum limits of hydrocarbons in soils and specifications for their characterization and remediation.
9. **NOM-041-SEMARNAT-1993** [95]: Establishes the maximum permissible limits for the emission of pollutants from the exhausts of motor vehicles in circulation that use gasoline as fuel.
10. **NOM-081-SEMARNAT-1994** [95]: Establishes the maximum permissible limits for noise emission from fixed sources and their measurement method.
11. **NMX-ANCE** [109]: These standards apply to electrical systems and equipment, including tests for PV systems. In addition, they include the schematics and diagrams of essential components of PV systems, energy measurement, and installation of the bidirectional meter of CFE (both its connection to the low voltage network and medium voltage network).
12. **2013 Energetic Reform**

The new energetic reform proposed by the current administration includes, among other changes, the cancellation of self-supply contracts and contracts with external power producers (PEI) [110,111]. This would make CFE the only state agency in charge of controlling, dispatching, operating, selling electricity, and setting rates in the country. In addition, the reform proposes that the current electricity generation of 38% by the CFE and 62% by the private sector definitively change to 54% by the CFE and only 46% by the private sector [112].

On the other hand, CFE generation costs are approximately two times higher than those corresponding to private combined cycle power generators [113,114]. A reduction in electricity generation from renewable sources, contemplated by this initiative, would impact the final sale price to the residential, commercial, and industrial sectors (if approved without any change or modification).

However, everything indicates that this reform will not affect distributed generation projects with an installed capacity below 500 kW [114]. The only case in which the reform could affect a project would be if the user wanted to expand the installed capacity to a system above 500 kW, since this would require a permit and would be cancelled by the reform [114].

2.4.2. Economic Parameters

1. **Government incentives and special loans**: According to article 34 of the income tax law (ISR), users who invest in a clean energy project may deduct 100% of the assets acquired from ISR in the first year of the investment [115]. In addition, public and private investment funds can finance clean energy projects. For example, these financings can be through the Trust for the Saving of Electrical Energy (FIDE), a trust created by CFE and the industrial chambers to encourage the efficient use and saving of energy [116]. Two development banks that can be used for this project are the National Bank for Public Works and Services (BANOBRAS) and *Nacional Financiera* (NAFIN).
2. **Investment**: The investment analysis considers: PV modules, inverters, guarantees, supports, and installation. It is essential to mention that as part of the investment, infrastructure such as stairs, access platforms, and other civil works should also be considered, as well as the hiring of experts belonging to the Electrical Installations

Verification Unit (UVIE) and the Inspection Unit of the Electrical Industry (UIIE), for the revision and approval of the electrical installation.

3. **Return on investment (ROI)**: From the estimated budget, a calculation of the return on investment is made, which is considered the deduction from the ISR Law, estimated annual inflation for subsequent years, financing, if the company opted for any, the energy rate that the company pays, the estimated energy produced by the PV system, the cost for maintenance and operation, and commissioning.
4. **Savings**: Incorporating a PV system implies a reduction in billing costs due to solar energy generation. With the energy generated from PV solar systems, it is possible to save part of the electricity consumption and costs taken from the electrical network to operate the user's plant or plants.

The cost of solar generation does not depend on fuels or inflation, so the potential savings over 20 years (the estimated useful life of the PV system, although it could be more than 25 years) would be significant. This is because the use of the solar distributed generation system, interconnected to the CFE network, or the standalone system, only impacts the operation and maintenance costs since the cost of solar energy is fixed.

2.4.3. Population Acceptance

The acceptance by the population is one vital aspect of the successful implementation of renewable energy production [117]. Ref. [118] suggests three primary dimensions regarding the acceptance of RES: socio-political, community, and market. The first one is the broadest dimension and is primarily concerned with policymaking. Community acceptance deals with local stakeholders and issues. At the same time, market acceptance deals with the relationship between investors and consumers [119]. It must be considered that for rapid adoption of renewable energy, all three acceptance forms are aligned, and neither is enough.

Population acceptance also refers to the relationship between the user and the PV system, as it is essential that the user is aware of how the system works, how much power his solar panels are producing, and how his behavior can reduce energy usage and save money. This is also important for monitoring and providing timely maintenance.

According to ref. [120], other dimensions regarding population acceptance are:

- Occupational safety and health impacts;
- Public health impacts;
- Environmental effects (this paper considers these impacts in the sustainable section);
- Impacts on social, political, economic, and institutional processes.

Figure 8 shows the stages in which each social element is used and/or analyzed.

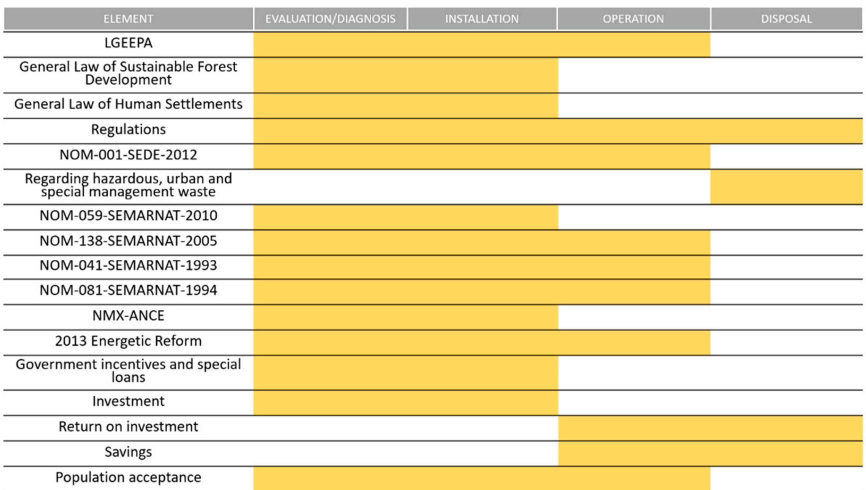

Figure 8. Social elements through the PV system stages.

3. Case Study

This case study demonstrates how companies can use this S4 framework to have a complete view of PV systems' lifecycles, allowing them to make decisions regarding the installation of PV systems. Thus, specific calculations are not shown. Using this framework, the specific calculation can be conducted using the S4 framework.

A medium-sized Mexican company wants to install a PV system on the roof of its production plant in Baja California, Mexico, to contribute to the corporate strategy of reducing the CO_2 footprint and to align with the new green advocate customers and governmental policies. Figure 9 (own elaboration with data from ref [121]) shows that the state of Baja California is the state with the highest potential to install PV systems in Mexico.

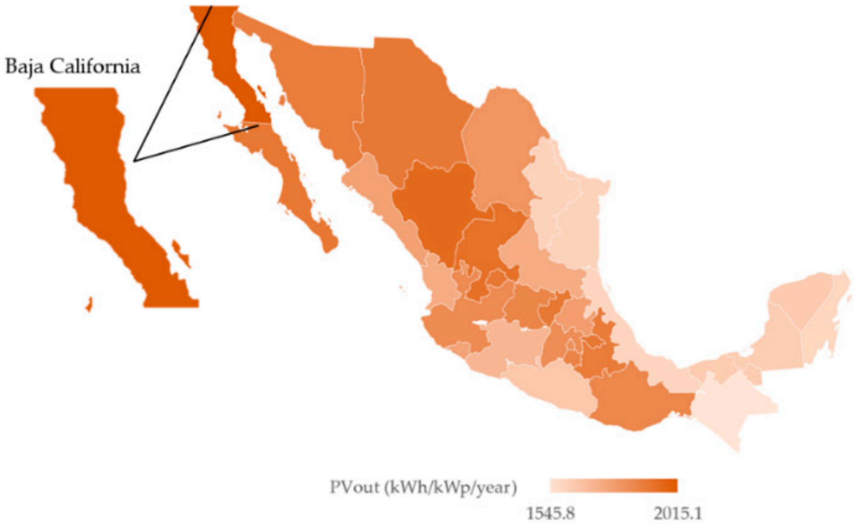

Figure 9. Photovoltaic power potential for Baja California, Mexico, 2019.

The Mexican manufacturing company needs to analyze whether the roof of its production plant is suitable for installing a PV system to produce part of the electrical energy required in the main building (lighting, air conditioning, etc.). It is essential to mention that the main production lines are not considered in the study because they require a constant amount of energy for 24 h, and storage systems are not considered in the PV system. As a result, considering its needs, the company decides to evaluate a grid-connected PV system (see Figure 10) as the most suitable type of connection with the main electrical grid.

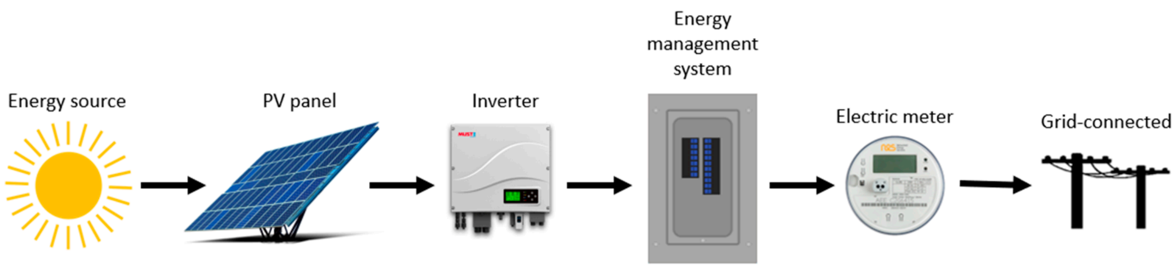

Figure 10. Grid-connected system for a medium-sized manufacturing company.

In addition, the project's economic and technical feasibility must be analyzed to decide on whether to install the PV system. To accomplish this study, the company considered the first approach following the conventional methodology presented below. It is essential to mention that this approach does not consider the S4 framework, but it provides the main elements to evaluate the installation and operation of the PV system in general terms. The conventional steps below do not use the S4 framework (from step 1 to step 12).

Step 1: Revise technical and environmental incentives derived from the distributed generation.

Step 2: Revise the legal and regulatory framework.

Step 3: Analyze the economic benefits.

Step 4: Define the PV system location, physical distribution, and energy required.

Step 5: Determine the type of connection (standalone or grid-connected).

Step 6: Define and analyze the meteorological and seasonal variables (mean irradiance, temperature, cloudiness, wind speed, and sun tilt) statistically to predict the system's operation. These variables were obtained from a weather station near the production plant; thus, the obtention of this information does not require sensors, but the values are not measured in the specific location.

Step 7: Analyze solar PV technology providers in the market, considering: efficiency, maximum power capacity, weight, size, lifespan, degradation by time and temperature of solar panels, and cost.

Step 8: Analyze PV panels' and inverters' CO_2 emissions.

Step 9: Analyze the structure of the ship/roof.

Step 10: Analyze statistically and predict the electrical energy generation.

Step 11: Analyze the reduction in CO_2 emissions per year.

Step 12: Analyze the inversion needed and its return considering governmental incentives.

As a result, it was determined that the roof area of the production plant usable to install the PV system would be 846 m^2, with 163 PV monocrystalline panels, and eight inverters to manage the energy generated from the panels would be installed. Additionally, it was decided that the support structure would be a fastening system for a corrugated sheet since one of the company's requirements was not to drill holes in the roof.

This first approach does not provide a complete view of all PV system stages (see Figure 2). Using the S4 framework, the company evaluated the system according to its needs and determined new objectives based on them. The company evaluated all the features and elements presented in the S4 framework. Hence, an updated version of the PV system was designed with the social, smart, sensing, and sustainable elements that best met the company's needs. This S4 framework does not require the results of the conventional approach since the S4 framework includes the information generated in the conventional approach.

4. Results and Discussion

Following the methodology proposed by the S4 framework, the manufacturing company considered a second approach and analyzed its technical and social needs deeply, and determined new objectives accordingly:

- Select sensors to measure meteorological and power variables for maintenance and monitoring purposes. Those sensors were not included in the conventional analysis.
- Select smart features to facilitate the decision-making process regarding the PV system. These elements provide a high level of automation of the PV system, but they were not integrated into the conventional proposal.
- Analyze environmental impacts considering all the elements involved at each system stage. In the conventional study, all the stages were not considered entirely and were considered only in general terms.
- Conduct a new analysis of the applicable laws and regulations and consider them.
- Analyze the energy and economic savings that will be generated.

After the new objectives were determined, the company analyzed each feature of the S4 framework, and, based on its needs, selected the features for each "S". Table 4 shows a comparison between the elements the company considered for the initial PV system following a conventional methodology, and the elements selected after using the S4 framework (the solution that best achieves the company's requirements).

Table 4. A comparison case study using a conventional method and the S4 framework method.

S4	Feature	Conventional Method	S4 Framework Method
Sensing	Panel surface temperature sensor		
	Solar radiation sensor		
	Voltage sensor		✓
	Current sensor		✓
	Air/ambient temperature sensor		
	Battery voltage sensor		✓
	Tilt angle sensor		
	Wind speed sensor		
	Wind direction sensor		
	Humidity sensor		✓
	Dust sensor		
	Rain/precipitation sensor		✓
	Load current sensor		✓
	Converter temperature sensor		✓
	A photovoltaic station weather system		✓
	Remote sensing and GIS	✓	✓
	WSN node		✓
Smart	Smart meter		✓
	Solar tracking system		
	Digital twins		
	Data storage		✓
	Data analytics		✓
	Predictive analysis		
	Monitoring system		
	Battery management system		✓
	Intelligent modeling techniques for forecasting solar energy		
	Smart inverter		✓
Sustainable	Solar panels' total CO_2 emissions	✓	✓
	Inverters' total CO_2 emissions	✓	✓
	Land use		
	Water use and consumption		✓
	Noise and visual disturbances		
	Impact on the flora and fauna		
	Waste management		✓

Table 4. *Cont.*

S4	Feature	Conventional Method	S4 Framework Method
Social	LGEEPA		
	General Law of Sustainable Forest Development		
	General Law of Human Settlements		
	Regulations	✓	✓
	NOM-001-SEDE-2012	✓	✓
	Regarding hazardous, urban, and special management waste		✓
	NOM-059-SEMARNAT-2010		
	NOM-138-SEMARNAT-2005		
	NOM-041-SEMARNAT-1993		✓
	NOM-081-SEMARNAT-1994		
	NMX-ANCE	✓	✓
	2013 Energetic Reform	✓	✓
	Government incentives and special loans	✓	✓
	Investment	✓	✓
	Return on investment	✓	✓
	Savings		✓
	Population acceptance		✓

As observed, the first approach that the company had toward a PV system considered only the fundamental elements of the installation and a partial analysis of other factors. This first approach mainly focused on the analysis cost, which is beneficial for getting the general evaluation of installing PV panels, but does not provide a detailed analysis of other elements involved in PV systems. Moreover, a clear view of the PV system's lifetime could not be entirely considered when a conventional methodology was used.

In the case of sensing features for measuring meteorological and seasonal variables, the company first considered data obtained from a weather station near the installation place instead of data collected directly in situ; as mentioned before, the data not obtained directly from the installation place can be inaccurate and cause alterations in the analysis, although a statistical analysis could give a more confident value approach. With the S4 framework, the company then decided to install a photovoltaic station weather system in the plant; this will allow them to obtain more precise meteorological data, analyze it more accurately, and make decisions during the entire lifespan of the PV system. Likewise, the company decided to install other sensors to monitor the entire system for maintenance purposes. Even though the system contemplated is a grid-connected type, the company is considering installing batteries for energy storage in the future, so they chose a battery voltage sensor to monitor the storage system correctly.

For smart elements, in the conventional approach, the company had no knowledge about smart features and how they can be integrated into PV systems. After implementing the S4 framework, the company decided to include features focused on data management and communication between the user and the monitoring system in the PV system. The smart elements chosen will allow the company to make predictions and effective decisions based on the system's state.

Initially, the company only considered the environmental impact of solar panels' and inverters' CO_2 emissions. Once the S4 framework analysis was made, the company added the environmental impacts of water use and consumption during the system operation and waste management once the system elements finished their lifecycle. The company did not consider the environmental impacts of land use, noise, visual disturbances, and impact on flora and fauna since the PV system will be installed on the roof of the production plant.

Because the PV system will be installed on the roof, there are some laws and regulations that are not applicable to this installation. The applicable regulations are mainly those related to the interconnection to the National Electric System, the safety of the users and the facility, the wiring, and the standards with which solar panels, inverters, and the installation must comply. In addition, the Energetic Reform should be considered if the system exceeds the installed capacity of 500 kW. The company did consider these regulations with the conventional approach; however, they did not consider regulations regarding waste management and emissions of pollutants from vehicles used during the system installation. Concerning the economic part, the investment and its return were considered; however, the savings from generating electricity instead of taking it from the grid were not estimated. Finally, population acceptance was not considered since there is no urban settlement near the installation place; however, in the S4 framework, this aspect was considered because it also considers the relationship between the user and the system.

With the S4 framework, small and medium-sized manufacturing companies can have a more comprehensive view of all the elements involved in PV systems considering their entire lifecycle. Compared with other reviewed frameworks, this framework integrates the sensing, smart, sustainable, and social features and their application in the Mexican context holistically. Similarly, the main difference between the S4 framework and conventional methods is that the traditional method focuses mainly on solar PV projects' economic and technical feasibility; a classification that considers all the features and elements of the PV system is not used. In contrast, the proposed framework analyzes all the technical and social aspects involved at each stage of the systems' life cycle using a complete classification that enables the best solution to be found.

5. Conclusions and Future Work

The use of solar energy in Mexican manufacturing companies is a viable option since it helps to diversify energy sources, improve efficiency, reduce environmental impact, and save money. Nevertheless, today there exists a gap in the literature since the currently proposed frameworks for solar energy mainly focus on technical and economic aspects that must be considered just in installing and operating PV systems. Thus, this paper proposes an S4 framework with the sensing, smart, sustainable, and social features involved in analyzing, installing, operating, and disposing PV systems for small and medium-sized companies in Mexico.

The primary function of this proposed S4 framework is that small and medium-sized companies can analyze each feature and its role in each stage of the PV system and, thus, choose the features that best meet their needs. Each feature is placed in an "S" according to its function; in this way, it is easier to analyze its role in each stage of the system.

As a result of this research, a case study was presented with a comparison between a manufacturing company considering a conventional approach to verify the technical and economic feasibility of installing a PV system on the roof of its production plant, and the same company using the approach of the S4 framework. After the two approaches were conducted, the company concluded that many aspects were not considered in the first approach, such as the measurement of meteorological variables in the installation place to obtain more precise data, the use of smart features for decision-making, and the analysis of other environmental impacts associated with the system. It is important to mention that the analysis made in the first approach did not consider the entire life cycle of the PV system either.

Therefore, with this framework, Mexican companies can analyze their technical and social needs regarding PV systems and energy, and select the S4 features that best meet those needs with the objective of obtaining the maximum efficiency of the system and better understanding each of its elements at each of the lifecycle stages.

Future work includes the integration of multicriteria decision-making, such as the Fuzzy TOPSIS method within the S4 framework, so that once the manufacturing company decides on the S4 features (elements), the Fuzzy TOPSIS method will help it to select the best solar panel company that can offer those S4 features and meet the needs of the manufacturing company.

Author Contributions: Conceptualization, C.P., P.P., A.M. (Alan Meier) and A.M. (Arturo Molina); methodology, C.P., P.P., A.M. (Alan Meier) and A.M. (Arturo Molina); validation, C.P., P.P., L.D., J.O.S. and J.P.; formal analysis, C.P., P.P., A.M. (Alan Meier) and A.M. (Arturo Molina); investigation, C.P., A.M. (Alan Meier), A.M. (Arturo Molina) and P.P.; resources, C.P., P.P., L.D., J.O.S., J.P. and A.M. (Arturo Molina); data curation, C.P. and P.P.; writing—original draft preparation, C.P.; writing—review and editing, C.P. and P.P.; visualization, C.P., P.P., A.M. (Alan Meier) and A.M. (Arturo Molina); supervision, P.P., A.M. (Alan Meier) and A.M. (Arturo Molina); project administration, P.P. and A.M. (Arturo Molina); funding acquisition, P.P. and A.M. (Arturo Molina). All authors have read and agreed to the published version of the manuscript.

Funding: This research project is supported Tecnologico de Monterrey, Mexico.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge the financial and the technical support of Institute of Advanced Materials for Sustainable Manufacturing, Tecnologico de Monterrey in the production of this work.

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

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