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Rainwater Harvesting Systems That Reduce Water Consumption With Optimal Locations of Solar Concentration Power Plants

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At present, the increase in population has caused an increase in the demand for electrical energy, which creates saturation in the national electrical system. In addition to this, the main source of energy for the generation of electricity is fossil fuels, which causes environmental pollution problems due to the increase in the concentration of greenhouse gases. To counteract the negative environmental impact, new energy sources that are friendlier to the environment have been sought, such as solar energy through power generation plants using solar concentrators. In this sense, this research proposes a mathematical optimization model to determine the feasibility of installing electric power generation plants through solar concentrators, to satisfy the energy demand in cities with the highest demand for electric power in the state of Michoacán. The proposed model considers the availability of water resources, the demand for energy, the costs involved for the installation of power generation plants, and the sizing of water collection systems to reduce the consumption of fresh water that is extracted from natural sources. It is a linear integer mixed programming model, where two scenarios are analyzed, considering variation in the operating time of the thermal storage system and the incorporation of the rainwater harvesting system to reduce freshwater consumption. The results show that 237,600 MW can be produced by installing three of the six power generation plants considered and considering a 19 h operation with thermal storage, generating a profit from the sales of the energy produced of 6,326,700 USD/year. Likewise, with the sizing of the rainwater harvesting system, it is possible to collect 1,678 m^3 for the operation of the three determined power generation plants.

Keywords: solar enegy, power energy, solar concentrator, rainwater harvesting system, optimization model

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INTRODUCTION

Currently, fossil fuels are the main ones to produce most of the mechanical and electrical energy sources, which are consumed around the world. However, the mitigation of the environmental impact due to emissions from the use of these fuels is inevitable; greenhouse gas emissions due to the consumption of conventional fuels are increasing disproportionately, and it is also expected that the energy production using fossil fuels in Mexico will be limited by 60% by the year 2035 (Vidal-Amaro et al., 2015). In this sense, the renewable energy resources with the greatest application around the world are hydraulic, wind, biomass, marine, geothermal, and solar (Benedek et al., 2018). Solar energy is the most abundant and available (Li et al., 2022) and can be harnessed in two ways: using heat (thermal conversion) or using light (in electrical–photovoltaic conversion or in natural lighting for buildings) (Kannan and Vakeesan, 2016). The first step for the use of solar energy is to process the radiation coming from the Sun, which can be carried out through two types of systems: passive systems or active systems (Sadhishkumar and Balusamy, 2014). The main active systems that are used are the thermal conversion elements, which comprise the heating harnessing sunlight, mainly the concentrators. In this sense, Ssemwanga et al., 2020, designed a hybrid solar dryer coupling an active solar photovoltaic obtaining higer efficiency in the drying process system. Ge et al., 2018 analyzed the future of solar applications in the heating and cooling system considering active solar systems. Kumar et al., 2019, realized a study of the solar application in the industrial process, and determined that the use of a solar energy system is an alternative to reduce fossil fuel sources. Joshi and Tiwari, 2018, considered the design of an active Solar System and heat exchanger for the water desalinization. Wu et al., 2019 designed an active Solar System considering parabolic concentrator and determined the thermal efficiency in the heat process from the Ssun's radiation. The concentrator technology is particularly distinguished by the shape and relationship of the concentrator and the receiver, such as parabolic trough concentrators, linear Fresnel concentrators, concentrators with a central tower receiver, and Stirling parabolic dishes. In the power energy generation, the most used are the central concentrator where the heat transfer fluid is in temperatures over 500°C (Guney, 2016). Beltagy et al., 2017, determined the parameters' design in the operation of the Fresnel solar concentrator and evaluated the possibility of power energy generation which can be carried out by increasing the area of the field. Santos et al., 2018, presented a study of the relevance of the solar concentrator systems in the power generation, considering that the parabolic Fresnel is a great alternative in the process for the conversion of the solar thermal energy. However, water is one of the main fluids used in both conventional and unconventional energy generation processes, added to this, not only is there currently little availability of energy resources but also a serious problem of water scarcity due to the increase in population (WWAP, 2017; Huang et al., 2021), which reduces the availability of freshwater resources. In this sense, multiple investigations have focused on finding new alternatives to reduce the consumption of water resources that is available for human consumption, considering alternatives of new sources to continue operating the energy process, analyzing problems such as water desalination (Panagopoulos, 2021) where the availability of water is related to the generation of energy. González-Bravo et al., 2016, proposed an optimization approach to define the optimal water distribution considering the overall sectors of water consumers. Ochoa-Barragán et al., 2021, determined an optimal distribution of water resources considering the natural sources of water available and the effect of incorporation of artificial sources to satisfy the demand in domestic and agricultural sectors. Considering that in the electrical power generation the main work fluid is water, the research are focused in reducing this water consumption. In this sense, Hamiche et al., 2016 analyzed the importance to identify the nexus with the water consumption and the industry mainly the power generation. Guo et al., 2021, proposed an optimization model to identify the optimal distribution of water sources in energy generation and water demand. Jamil et al., 2021, analyzed the freshwater reduction in the cooling process applied in thermal plants for power generation. The importance of minimize the water consumption in power energy generation represents a challenge to consider, in this sense, Tan et al., 2021 proposed a stochastic model to determine the optimal energy generation considering water conservation policy and the emission reduction of greenhouse gases. In this sense, the present research proposed the use of renewable energy sources that allow a self-sustaining increase in the generation of electrical energy. The solar active system is considering, with solar concentrator plants. Through a mixed-integer linear programing (MILP) optimization approach, we can identify the feasibility of installing solar thermal power plants to generate electricity and increase the coverage of the electrical system, the power energy generated will be fed into the national grid system, for these reasons, the mathematical model proposed maximizing the total annual profit considering the possible installation plants, the associated costs, and the possible electrical energy that can be generated, as well as satisfy the growing demand for electricity, incorporating fresh water sources available, and the effect of incorporating the rainwater harvesting system evaluating the potential and dimension of catchment systems. This research evaluated the potential for reducing the consumption of fresh water in the electric power generation. This proposal can be a sustainable solution to the generation of current energy, since the economic aspect is considered; reducing the costs involved in the installation of electric power generation plants. In the social aspect, a greater availability of electric energy is provided, which can bring better human development, and in the environmental aspect, it seeks to improve environmental conditions through the reduction of fossil resources in the generation of energy, in the same way reducing the consumption of resources can compromise the resources available for future generations, as in the case of water.

METHODOLOGY

The heliostat field captures solar radiation and reflects it onto an absorber or receiver that is located at the top of a tower located in the center of the heliostat field. A heat-conducting fluid circulates through this receiver, which, for the case of the plant analyzed in this work, is water. All the radiation reflected by the heliostats is transmitted to this fluid, thus converting solar energy into thermal energy, heating the fluid to more than 500°C. The already heated fluid is sent, either, if available, to the thermal store, which allows the plant to continue operating hours after sunset and on cloudy days, or directly to the turbine. The generation of electrical energy occurs through a steam or Rankine cycle, where there is a turbine coupled with an electric generator. The turbine rotates by

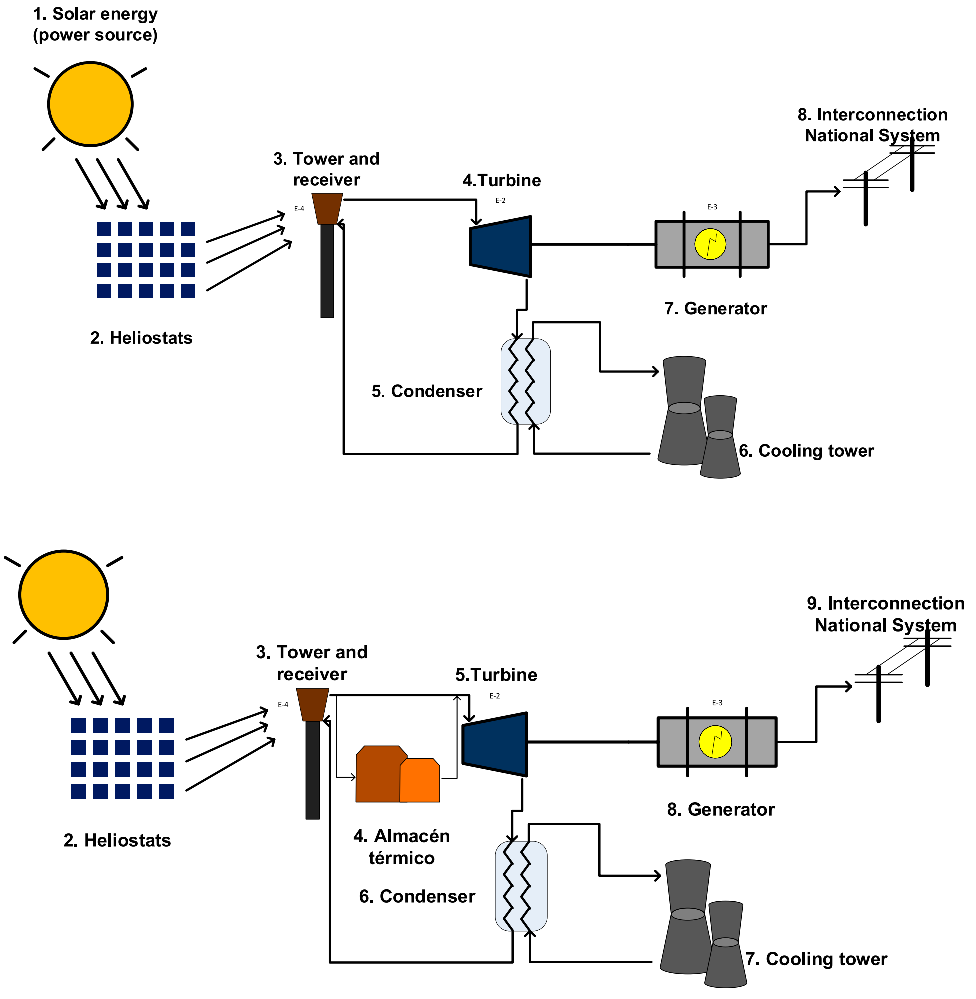

FIGURE 1 | Stages in the generation of electrical energy through solar concentrators, with and without thermal storage systems.

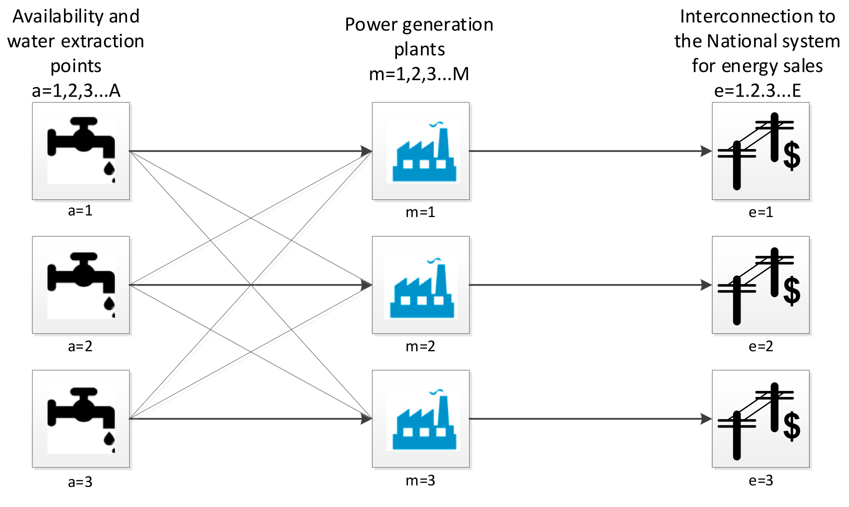

FIGURE 2 | Superstructure for the case study for the optimal location of power generation plants with solar concentrators.

means of the kinetic energy of the water vapor heated by solar radiation. When it rotates, this energy is transformed into electricity thanks to the generator. The electrical energy produced is conducted to a transformer that sends it to where it is demanded. The present work considers power plants of the type of central tower receiver with a circular heliostat field, as showed in **Figure 1**, due to the distance that exists between the location of the project and the line of the equator. **Figure 2** shows the superstructure to determine the optimal configuration for the optimal location of power generation plants with solar concentrators in the state of Michoacán, Mexico, the superstructure considering the extraction points of water for the steam generation in plants and the feasibility of supplying the energy generated to the network of the national electrical system.

Model Formulation

Figure 2 shows the proposed superstructure for the mathematical model, where we define the following sets: the set a represents the availability and extraction points of the water flow to feed the power generation plants, they are defined in set m, in which the flow of water through the action of the plant systems is converted into energy flow at the outlet to be marketed through interconnections to the national system network, this process is defined in set e, and finally, the set t represents the time intervals equivalent to the months of the year. For the mathematical formulation, the following systems are established: pretreatment system, tower system, turbine system, condenser system, and cooling tower system.

The balance to quantify the availability of water is determined through the following equation:

$$FTW_{a,t} = \sum_{m \in M} FTEP_{a,m,t}, \forall a \in A, t \in T. \tag{1}$$

In the previous balance (**Eq. 1**) the $FTW_{a,t}$ indicates the total flow of water from the extraction points a in a period t, this flow is sent to the plant m for the generation of electricity.

The following equation determines the flow of water that enters the pretreatment system within the plants:

$$FWPT_{m,t} = \sum_{a \in A} FTEP_{a,m,t}, \forall m \in M, t \in T. \tag{2}$$

To establish an input value for the input flow to the system, the following restriction is proposed, to establish a limit of water access to the electric power generation system.

$$FWPT_{m,t} \leq FMAXPT_{m,t}, \forall m \in M, t \in T. \tag{3}$$

Once the flow that enters in the pretreatment system is determined, the flow that enters the tower is established to the tower system, through the following balance:

$$FWTR_{m,t} = FWPT_{m,t} \cdot \alpha TR, \forall m \in M, t \in T. \tag{4}$$

In previous balance, αTR is a parameter that indicates the water loss factor during the process in the tower system.

The water flow in the turbine–generator system is represented by the following equation:

$$FWTU_{m,t} = FWTR_{m,t} \cdot \alpha TU, \forall m \in M, t \in T. \tag{5}$$

Additionally, a parameter is considered that indicates the water loss factor in the process of the turbine–generator system αTU.

In the following balance, the energy flow at the generator output is determined:

$$FETU_{m,t} = \frac{FWTU_{m,t}}{DU}, \forall m \in M, t \in T. \tag{6}$$

In the previous equation, DU is a parameter that indicates the quantity of fluid necessary to determine the energy that can be generated by the transfer of thermal energy that the fluid has.

The following balance determines the flow in the condenser system:

$$FWCO_{m,t} = FWTU_{m,t} \cdot \alpha CO, \forall m \in M, t \in T, \tag{7}$$

where αCO represents a parameter that indicates the water loss factor during the process in the condenser system.

The energy flow that enters the interconnection system to the national grid is established from the following equation:

$$FEMERC_{e,t} = \sum_{m \in M} FE_{m,e,t}, \forall e \in E, t \in T. \tag{8}$$

The following equation determines the benefit obtained from energy sales per plant:

$$SALES_{e,t} = FEMERC_{e,t} \left(0.98 \cdot \beta \, \mathrm{cost} E_{e,t}\right), \forall e \in E, t \in T, \tag{9}$$

where $\beta \cos t E_{e,t}$ represents the unit price for each MWh injected into the network, which according to the National Interconnected System varies according to the proposed locations for the power plants and is multiplied by 0.98 because it is considered a system through a contract by the CRE, which establishes that only a supply of 98% of the total generation of the plant is approved.

The operation and maintenance costs of the various systems are determined considering a unitary operational cost $U\mathrm{Costop}PT_{m,t}$ and the flow in each system, the cost is defined by the following equation:

$$CostopPT_m = \sum_{t \in T} FWTP_{m,t} \cdot U\mathrm{Costop}PT_{m,t}, \forall m \in M. \tag{10}$$

In the following equation, a disjunction is proposed, considering the Boolean variable Y_{EN}, this variable is taken as the decision variable, since it can help us define when a solar concentration plant is installed. If the flow of fresh water and the costs associated with its installation exist, it means that these restrictions are true and the Boolean variable is true; otherwise, if there is no flow, no costs are associated with it and the Boolean variable is false. This disjunction takes into account the capital cost of each of the plant systems, which are given by the fixed costs and the variable part; the capital cost that refers only to the cost of the equipment used and a variable cost that refers to the cost of managing or adapting the flow that is being processed. In this sense the variable part is multiplied by the flow processed in each system.

$$\begin{bmatrix} Y_{EN} \\ FWTP_m^{CAP_{\min}} \le FWTP_m^{CAP} \le FWTP_m^{CAP_{\max}} \\ CostcapPT_m = CostFIX_m^{PT} + CostVAR_m^{PT} \cdot FWTP_m^{CAP} \\ CostcapTR_m = CostFIX_m^{TR} + CostVAR_m^{TR} \cdot FWTR_m^{CAP} \\ CostcapTU_m = CostFIX_m^{TU} + CostVAR_m^{TU} \cdot FWTU_m^{CAP} \\ CostcapCO_m = CostFIX_m^{CO} + CostVAR_m^{CO} \cdot FWCO_m^{CAP} \\ CostcapTE_m = CostFIX_m^{TE} + CostVAR_m^{TE} \cdot FWTE_m^{CAP} \end{bmatrix} \times \begin{bmatrix} \neg Y_{EN} \\ FWTP_m^{CAP} = 0 \\ CostcapPT_m = 0 \\ CostcapTR_m = 0 \\ CostcapTU_m = 0 \\ CostcapCO_m = 0 \\ CostcapTE_m = 0 \end{bmatrix} \forall m \in M. \quad (11)$$

However, for the encoding of the proposed model is considered to be an algebraic reformulation convex hull (Raman and Grossmann, 1994) to linearize the previous disjunction, the Boolean variable is reformulated by the binary variable y_{EN}. In this case when a flow of fresh water and cost associate with the installation of plants exist, the binary variable take a value of one, otherwise the binary variable is zero and the plant is not installed. This is obtained by the following equations:

$$FWTP_m^{CAP_{\min}} \cdot y_{EN} \le FWTP_m^{CAP} \le FWTP_m^{CAP_{\max}} \cdot y_{EN}, \forall m \in M, \quad (12)$$

$$CostcapPT_m = CostFIX_m^{PT} \cdot y_{EN} + CostVAR_m^{PT} \cdot FWTP_m^{CAP}, \forall m \in M. \quad (13)$$

Finally, is defined the transportation cost generated by the piping and pumping of water, from the extraction point to the power plants, is considering a unitary transport cost:

$$CostTransport = \sum_{a \in A} \sum_{m \in M} \sum_{t \in T} FWTP_{a,m,t} \cdot UnitTransp_{a,m} \cdot Dist_{a,m}. \quad (14)$$

The mathematical model proposed is defined to the maximization of the objective function. In this objective, the function is declared by the variable PROFIT, that, considering the sales of the energy supplied to the national grid and the total costs involved for power generation, the objective function is established by the following equation:

$$COSTOT = \sum_{m \in M} CostopPT_m + \sum_{m \in M} CostcapPT_m + CostTransport, \quad (15)$$

$$PROFIT = \sum_{e \in E} \sum_{t \in T} SALES_{e,t} - COSTOT. \quad (16)$$

The proposed mathematical model seeks to establish the feasibility of installing electric power generation plants through solar concentrator systems. The effect is determined by the use of water, which is the main working fluid for power generation.

RESULTS AND DISCUSSIONS

To show the applicability of the mathematical model proposed, the installation of solar thermal power plants is considering the case study, with a central tower receiver, and three possible locations for their installation in the state of Michoacán, Mexico. Michoacán is a state belonging to the central-western region of the country and one of the states that consumes the most electrical energy, with an approximate consumption of 6,794 GWh, however, the state only produces 2,779 GWh. Due to the exaggerated population growth, the state is therefore in the demand for electrical energy. For the possible installation of the plants, there is great interest in six locations in the regions of the Lerma–Chapala region, the Cuitzeo region, and the Sierra–Costa region. The criteria to establish a possible installation site for a power generation plant was that it would be close to a freshwater extraction point, since it is the main workflow for the operation of the plant, and that it would be close to the cities with the highest demand for electricity, in order to reduce losses in the process of distribution of electricity. The interest in these regions is because they are in the 3 municipalities that demand the most electricity in the state (Lazaro Cardenas, Morelia, and Zamora). Also, for purposes of analysis for the potential of usable solar radiation and the availability of water, necessary supplements for plant operation are to be given. The deterministic model MILP proposed is coded in the software GAMS through the solver CPLEX (Brooke et al., 2012), used to solve the mixed-integer linear programing (MILP) problem. The addressed case study has 517 continuous variables, 1 binary variable, and 525 constraints. The model was solved in a computer with the Intel® Core™ i7 processor at 2.80 GHz with 12.0 GB of Memory RAM with a 0.016 s of CPU time in each scenario. The proposed model seeks to find the optimal level of operation according to the thermal storage system, determine the optimal amount of installation of power generation plants according to the availability of water resources in the surroundings, the amount of profits obtained by the electrical energy generated and that is fed into the network of the national energy system, and determine what is the flow of rainwater that can be captured for the reduction of fresh water without harming the operation of the electric power generation plants through solar concentrators. Two scenarios are proposed. The first scenario contemplates the optimal energy generation considering several operational times in the thermal storage system, and in the second scenario, an economic benefit analysis is carried out to calculate the return on investment in the installation of power generation plants.

Scenario A: Optimal Power Generation Modified the Operation Times in the Thermal Storage System

This scenario presents the optimal solution of the installation of solar concentrator plants, considering the

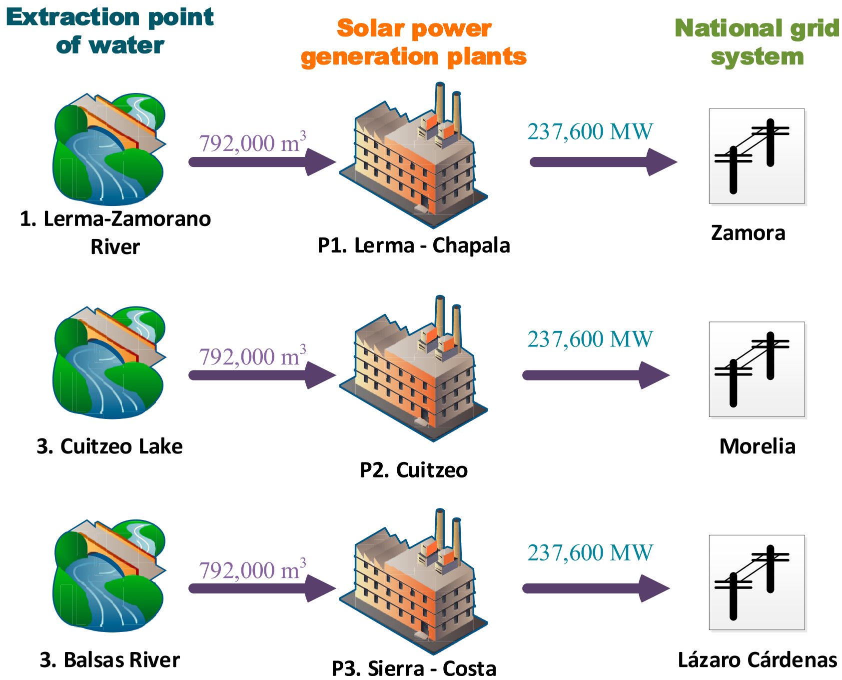

FIGURE 3 | Optimal distribution of scenario A, for the installation of solar concentration plants for electric power generation for case d (24 h of operation with 19 h of thermal storage).

TABLE 1 | Cost involved in the solar power generation plants.

Concept	Cost (US$)	% of total
Heliostats	46,200,000	25.895
Wiring and equipment	2,081,540	1.167
Ground	25,314,222	14.188
Civil work	21,335,508	11.958
Edging and adjustment	4,150,559	2.326

following operation times in the thermal storage system: 1) 5 h of operation without a thermal storage system, 2) 8 h of operation and contemplating 3 h of thermal storage, 3) 16 h of operation with 11 h of thermal storage, and 4) 24 h of operation with 19 h of thermal storage. The results show the feasibility of installation of three plants of the six considered for cases for the electric power generation (Plant 1. Lerma–Chapala, Plant 2. Cuitzeo, Plant 3. Sierra–Costa), the electric generation increase with the increase of the thermal storage system, the optimal distribution is showed in **Figure 3**. This figure shows the optimal distribution found for the case d, which represents the configuration with highest energy production; this configuration considers the extraction points of fresh water (1. Lerma–Zamorano River, 2. Cuitzeo Lake, and 3. Balsas River) that are fed to the plant for power generation. The plants involved take into account the same water extraction with a water flow of 792,000 m^3 and the same electricity generation of 237,600 MW because they have the same capacity, because the plants operate in the same way. Also, this configuration established the places where it is feasible to install three power generation plants through solar concentrators founded in the solution of the model proposed and finally the amount of energy that is generated in the installed plants that can be fed into the national energy network is calculated. For the economic analysis of the solar field, the first data to be considered are the cost of the heliostats, as well as the costs involved for their installation (Caminero Ocaña, 2014). For practical purposes, the total cost of the solar field, including heliostats, is broken down in the analysis of **Table 1**. According to previous information, the maximum energy generated is presented in the case with the highest thermal storage (case d) with a production of 237,600 MW, however, is the case with more use of water, as show in **Table 2**. The high production in case dpresents greater feasibility of energy production due to the incorporation of the thermal storage system, since without it, the generation process is not very feasible due to the low global efficiency in the system. However, despite being the solution with the highest energy generation, it is the one with the highest operating costs due to the implementation of the thermal storage system. In all cases, negative gains are presented until the first year of operation, however, in all cases, the energy generation is considerable, but a better effect is visualized considering the thermal storage system. The sales by the amount of energy supplied to the national grid is from 6′326,700 USD/year for the case a, to 30′368,000 USD/year for the case d. The profits for the three plants considered: 1.16×10^7 USD/year for plant 1, 2.19×10^7 USD/year for plant 2, and 3.19×10^7 USD/year for plant 3. These profits are obtained by operating with 19 h of thermal storage, which favors a greater

TABLE 2 | Total flow of new species used in biofuel production.

Case	Location plants	Electrical energy generated (MW)	Sales for electrical energy (USD/year)	Flow of water (m^3/year)
a	1. Lerma—Chapala 2. Cuitzeo 3. Sierra - Costa	49,500	6,326,700	165,000
b	1. Lerma—Chapala 2. Cuitzeo 3. Sierra - Costa	79,200	10,122,000	264,000
c	1. Lerma—Chapala 2. Cuitzeo 3. Sierra - Costa	158,400	20,245,000	528,000
d	1. Lerma—Chapala 2. Cuitzeo 3. Sierra - Costa	237,600	30,368,000	792,000

TABLE 3 | Monthly precipitation in the state of Morelia, Mexico.

Month	Precipitation (mm)
JAN	6.8
FEB	29.8
MAR	9
APR	5.1
MAY	9.8
JUN	92.5
JUL	155.9
AUG	201
SEP	167.6
OCT	20.2
NOV	2.9
DEC	2.4

generation of energy; however, due to the high feasibility of generating electricity, it is the case in which more water is processed in the system, processing approximately 792,000 m^3/year per plant.

Scenario B: Rainwater Harvesting System Incorporation

This scenario presents the rainwater harvesting system incorporation to reduce the consumption of fresh water in the process of generating electricity. Considering that the state of Michoacán is one of the states that has one of the highest rates of rainfall, the percentage of water that can be recovered is evaluated, as well as the feasible area for the implementation of the system. The solution of this scenario considering the recent values reported of precipitation indices evaluated in the year 2020 in the annual report by CONAGUA 2021, is shown in **Table 3**. Considering these values, the possibility of covering the demand for fresh water in the system through rainwater is established, so **Figure 4** shows the areas obtained from some scenarios to cover from 10 to 100% of the demand for fresh water. It is possible to observe that in the months with less precipitation, the necessary areas of the rain catchment system present very large areas, which is why it is infeasible, especially if it is required to cover 100% of the demand for fresh water. In order to determine a feasible

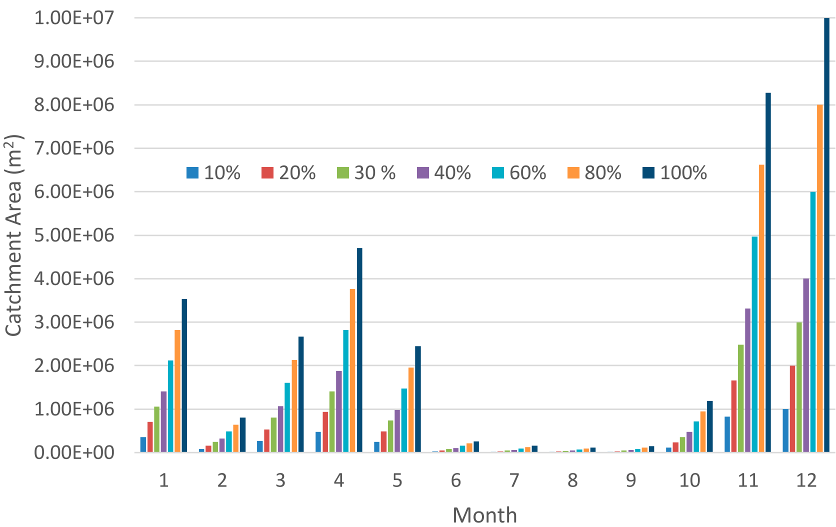

FIGURE 4 | Catchment area for the rainwater harvesting system considering the precipitation and demand covering of fresh water.

TABLE 4 | Length to the rainwater harvesting system considering variation in the percentage of demand for fresh water.

Month	Length (m)			
	10%	3%	2%	1%
1	11764.706	3529.412	2352.941	1176.471
2	2684.564	805.369	536.913	268.456
3	8888.889	2666.667	1777.778	888.889
4	15686.275	4705.882	3137.255	1568.627
5	8163.265	2448.98	1632.653	816.327
6	864.865	259.459	172.973	86.486
7	513.149	153.945	102.63	51.315
8	**398.01**	**119.403**	**79.602**	**39.801**
9	477.327	143.198	95.465	47.733
10	3960.396	1188.119	792.079	396.04
11	27586.207	8275.862	5517.241	2758.621
12	33333.333	10000	6666.667	3333.333

catchment area, various cases were resolved considering a lower demand for fresh water coverage. For these reasons, it was established to determine the area of a surface, considering a fix width of 30 m. **Table 4** shows the possible length of the rainwater harvesting system according to the monthly precipitation and percentage satisfaction of the demand for fresh water for the solar concentrator plants. Some areas are feasible as the case of 2% of coverage results in a catchment area of 2,388 m^2, this area represent the months with the highest precipitation. However, by establishing this system with a fixed area throughout the year, it would be possible to collect a volume of rainwater of 1,678 m^3.

CONCLUSION

In this article, an optimization methodology was presented to determine the optimal location of electric power generation plants from solar concentrator plants in the state of Michoacán. The results show that the generation of energy through solar concentrators is favored considering operation with a thermal storage system, since without this system, there is less operation time considering only the hours of available sunlight. The solution of the model proposed the installation of 3 of the 6 solar plants considered. The better value of energy generated was the option d with a thermal storage operation of 19 h. This configuration presented an energy production of 237,600 MW. The profits for the three plants considered was 1.16 $\times 10^7$ USD/year for plant 1, 2.19 $\times 10^7$ USD/year for plant 2, and 3.19 $\times 10^7$ USD/year for plant 3. In addition, the amount of freshwater flow supplied to the plant was determined and the dimensions of rainwater storage systems were identified to reduce freshwater consumption, showed in **Table 4**. According to the data on rainfall in the state, the optimal value rainwater recovery is 2% of coverage with a catchment area of 2,388 m^2. With this rainwater harvesting systems, it is possible to collect a volume of rainwater of 1,678 m^3 per year. For this reason, the result considered that it is feasible to install rainwater storage systems, allowing freshwater consumption to be reduced by 0.6% per year. Considering the installation of rainwater storage systems is feasible, the installation of power generation plants forms solar concentrator, the energy supply at the grid of the national system, will be significant in reducing the demand of electricity from conventional sources.

The model proposed is a deterministic optimization model, however, in future work uncertainty factors can be added. Two scenarios that are proposed could be considered an uncertainty in the price of MW, since in the Mexican electrical system, the price varies with respect to the daily hour. There are hours with high demand for electrical energy so the MW that is supplied to the network is valued at a better sale price. This could improve the economic results in terms of profit maximization since it could be determined at what times it is more convenient to generate energy and supply it to the national grid.

Similarly, uncertainty could be considered in the precipitation levels throughout the year, although in this model it only considers the precipitation values for the year 2020. A dataset could be implemented to predict which would be the values with the highest precipitation for the years subsequent and thus define what would be the volume of rainwater that could be captured. This leads to proposing a more robust mathematical optimization model. Two stages are established; in the first stage, a stochastic model is proposed, in which the uncertainty effect due to the variation in the price of MW in relation to the objective function is evaluated. This will generate multiple solutions, and through a pareto chart, you can visualize optimal solutions for the objective function. In the second stage, the solutions previously found are compared with the solutions for the deterministic model without the uncertainty effect in such a way that it is observed if it is possible to obtain better solutions under uncertainty. Finally, the same methodology applies to the uncertainty effect on precipitation levels but is related to the catchment area.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

PE-MA proposed the idea, carried out the conceptualization, wrote the original draft, and conducted formal analysis. MA-CG was responsible for the coded model proposed, analysis of the data, and design of the case studies.

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NOMENCLATURE

Indexes

a Index for extraction points of the water flow

m Index for power generation plants with solar concentrators

e Index for marketed in the national system network

t Index for time periods

Sets

A Set for extraction points of the water flow a

M Set for power generation plants with solar concentrators m

E Set for marketed in the national system network e

T Set for time periods t

Parameters

αCO Loss factor of water in the condenser system of the plant m

αTR Loss factor of water in the tower system of the plant m

αTU Loss factor of water in the turbine system of the plant m

$\beta \cos \mathbf{t} E_{e,t}$ Energy price (MWh) in energy cities e

DU Factor of energy generation in the plants m

$CostFIX_m^{CO}$ Fixed cost for the condenser system in the plants m

$CostFIX_m^{PT}$ Fixed cost for the pretreatment system in the plants m

$CostFIX_m^{TE}$ Fixed cost for the thermal storage system in the plants m

$CostFIX_m^{TR}$ Fixed cost for the tower system in the plants m

$CostFIX_m^{TU}$ Fixed cost for the turbine system in the plants m

$CostVAR_m^{CO}$ Unit variable cost for the condenser system in the plants m

$CostVAR_m^{PT}$ Unit variable cost for the pretreatment system in the plants m

$CostVAR_m^{TE}$ Unit variable cost for the thermal storage system in the plants m

$CostVAR_m^{TR}$ Unit variable cost for the tower system in the plants m

$CostVAR_m^{TU}$ Unit variable cost for the turbine system in the plants m

$FWTP_m^{CAP_{\max}}$ Maximum water flow in the plants m

$FWTP_m^{CAP_{\min}}$ Minimum water flow in the plants m

$Dist_{a,m}$ Distance from extraction points a to the plants m

$UnitTransp_{a,m}$ Unit transportation cost of water flow to the plants m

$U\mathbf{Costop}PT_{m,t}$ Unit operating cost for the plants m

Variables

$CostcapCO_m$ Capital cost for the condenser system in the plants m

$CostcapPT_m$ Capital cost for the pretreatment system in the plants m

$CostcapTE_m$ Capital cost for the thermal storage in the plants m

$CostcapTR_m$ Capital cost for the tower system in the plants m

$CostcapTU_m$ Capital cost for the turbine system in the plants m

$CostopPT_m$ Operational cost for the plants m

$COSTOT$ Total cost involved

$CostTransport$ Cost for transportation

$FE_{m,e,t}$ Energy flow supplied to the network e from the plants m

$FEMERC_{e,t}$ Energy flow supplied to the network e

$FETU_{m,t}$ Energy flow generated in the plants m

$FMAXPT_{m,t}$ Maximum input water flow in the plants m

$FTEP_{a,m,t}$ Water flow from each extraction point a to the plants m

$FTW_{a,t}$ Water flow considered in each extraction point a

$FWCO_{m,t}$ Water flow in the condenser system of the plants m

$FWCO_{m,t}$ Water flow in the pretreatment system of the plants m

$FWTP_m^{CAP}$ Water flow for the dimensions of the plants m

$FWTR_{m,t}$ Water flow in the tower system of the plants m

$FWTU_{m,t}$ Water flow in the turbine system of the plants m

$SALES_{e,t}$ Total sales for the energy flow supplied to the network e

$\mathbf{PROFIT}$ Total annual profit

y_{EN} Binary variable for the existence of the plants m

Y_{EN} Boolean variable for the existence of the plants m