EXERGY MAPS AS A TOOL FOR ASSESSING SOLAR ENERGY POTENTIAL IN MÉXICO

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ABSTRACT

Mexico is one of the countries with the most significant solar resources; however, significant development of solar thermal and photovoltaic installations still needs to be done in this country. Solar resource estimation is fundamental to achieving the efficient use of solar energy since this will allow the adequate dimensioning of the solar energy systems, both photovoltaic and solar concentration systems. In Mexico, there is a national network of solar measurement stations; however, it would be practically impossible to have a network to estimate the solar resource with greater precision through measured data. An alternative to meteorological stations is estimating solar radiation with satellite data. Some geostationary satellites, such as the GOES-R series, are equipped with sky cameras and sensors that determine atmospheric variables such as shortwave and longwave radiation. The estimation of solar radiation using satellite data has been developed in recent years using increasingly precise equipment and systems. However, it is essential to evaluate not only the solar resource, which includes direct and diffuse radiation, but also to determine the potential of energy generation and the availability of energy in specific locations; this means determining the exergy potential inherent to solar radiation. Therefore, the work described in this paper has two important innovations: a) Estimate the average solar radiation in the Mexican Republic using the DSR (Downward shortwave irradiation, product ABI-L2 of the GOES-16 satellite data. b) Introduces a pioneering map illustrating the exergy potential inherent in solar radiation in Mexico. This unique exergy potential is derived using a specialized model designed to estimate the utmost efficiency of solar radiation conversion into usable work.

1 INTRODUCTION

In the pursuit of optimizing solar energy utilization, the accurate assessment of solar resources emerges as a pivotal concern. Such assessments facilitate the proper sizing and design of solar energy systems, encompassing photovoltaic arrays and solar concentration installations. Noteworthy studies, such as that by Ho et al. (2011), underscore the substantial impact of solar radiation calculation uncertainty, attributing approximately 45% of performance variation in solar concentration plants to this factor. Consequently, a compelling imperative arises for enhanced precision in measurement techniques and modeling frameworks to refine the estimation of this invaluable resource.

Having a network of meteorological stations allowing direct and diffuse solar radiation measurements is extremely important; however, it would be impossible to have a network to estimate solar resources with greater precision through measured data. Particularly in Mexico, there is a national network for solar measurement stations. This network was promoted by the government and some research institutions, like the National Autonomous University of Mexico (UNAM), the Mexican Center of Innovation in Solar Energy (CEMIE-SOL), the National Council for Science and Technology (CONACYT), among others.

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Moreover, the solar radiation database Meteonorm emerges as a prevalent tool for estimating solar resources for designing solar thermal and photovoltaic systems and building simulations (METEONORM, 2020). It finds application both as standalone software and as an integrated component within popular simulation platforms like Polysun. Nevertheless, as noted by Remund & Müller (2011), an uncertainty of up to 8% may persist, particularly for sites lacking proximate ground measurements. In addition, this database is paid, and the free version is minimal.

Therefore, during the last decades, satellite images have been used to study clouds, their composition, and their effect on radiation attenuation. Some geostationary satellites, such as those of the GOES-R series, are equipped with a series of sky cameras and sensors that determine atmospheric variables such as surface temperature, humidity, precipitation, and shortwave and longwave radiation, among others. (Alonso-Montesinos et al., 2015, Escrig et al., 2013).

Solar radiation estimation using satellite data has been developed using increasingly precise equipment and systems in recent years. There are works such as that of Sözen et al. (2004), who estimated the solar energy potential in Turkey using ANN and meteorological data. A study in Algeria developed by Yacef et al. (2014) analyzed global radiation for clear sky conditions. One of the most consolidated models for estimating solar radiation with clear skies is the one developed within the framework of the ESRA (European Solar Radiation Atlas), which used the Heliostat model (Diabaté et al., 1987), presenting reasonably accurate results (Bosch et al., 2010). Regarding the application of data from the GOES-16, there is the work of Jiang Chen et. Al. (2021); in this work, the authors use the Random Forest method to estimate and map half-hourly DSR at 1 km spatial resolution over the Continental United States (CONUS), observing that the results obtained are similar spatial patterns with the results from the Clouds and the Earth's Radiant Energy System (CERES).

Talking about the estimation of solar radiation using satellite data in Mexico, there are some other works like the one of Enríquez-Velásquez et al. (2020), who carried out an investigation to obtain the distribution of solar radiation in the state of Sonora and proposed this model as a valuable tool for providing specific, low-cost and reliable data for a broad and detailed view of solar radiation. There is also the work of (Ulloa-Godinez et al., 2017), who evaluate the climatological aspects of incoming solar radiation under clear sky conditions in Jalisco, the State of Mexico, and the Guadalajara Metropolitan Area.

As can be seen, estimating solar resources through satellite data is an increasingly used tool. However, it is imperative to assess the solar resource encompassing direct and diffuse radiation and ascertain the energy generation potential and availability at specific locations, which entails evaluating the inherent exergy potential of solar radiation. Notably, studies such as Joshi et. al. (2014) have endeavored to estimate the solar exergy radiation for both photovoltaic and thermal systems, as exemplified in the case of New Delhi.

In the same context, over the past six decades, many models have been proposed to quantify the maximum conversion process of solar energy into work. Diverse methodologies have been explored, including Petela's consideration of a cylinder-piston system with photon gas (Petela R., 1961), Spanner's use of Brønsted's definition to compute work in a leaf (Spanner D.C., 1964), and Press's analysis of a cylinder-piston system considering both direct and diffuse radiation (Press, 1976). Other researchers like Parrot (1978) and Bejan (1987) have modified these models, introducing considerations such as the directionality of photon gas and the necessity for continuous work extraction. Recent advancements have led to the development of a comprehensive model within the framework of endoreversible thermodynamics (González-Mora et al., 2023). This novel model, designed for Concentrated Solar Power (CSP) systems, considers environmental temperature and solar concentration geometry, incorporating elements such as Concentration-Acceptance Product (f_H) and direct normal irradiation (DNI). This breakthrough provides a more accurate estimation of the maximum efficiency in converting solar radiation into usable work.

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Therefore, the main objective of this paper is to construct solar exergy maps for various regions across Mexico, employing the model proposed by Gonzalez-Mora et al. (2023). These maps will depict the available useful energy across different geographical locations, thereby elucidating a critical parameter essential for enhancing the efficiency of solar-based systems.

2 METHODOLOGY

As mentioned, we will use satellite data to determine the radiation exergy in this work. To achieve this objective, we follow the methodology shown in Fig. 1, which is described below.

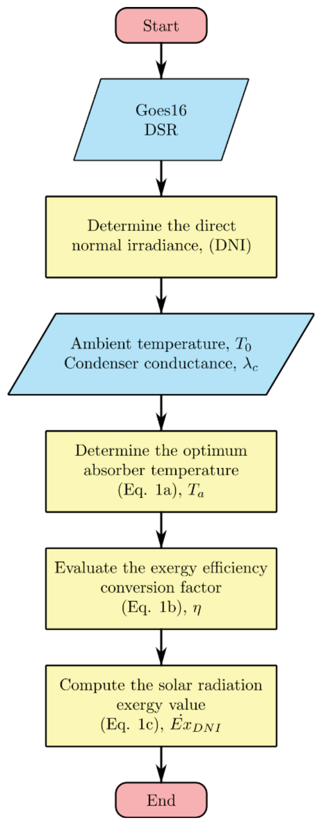

Figure 1: Methodology for the estimation of the exergy potential of solar radiation in Mexico

The initial step involved is to estimate solar radiation across the Mexican Republic utilizing Downward Shortwave Irradiation (DSR) product derived from the GOES-16 satellite data (NOAA, 2019) in the CONUS region. DSR is an intermediate-level product that provides an estimation of the total shortwave irradiance received per unit of horizontal area on the Earth's surface, encompassing both direct and diffuse radiation. The spatial resolution of this product is detailed in Table 1. Notably, validation of this product has been conducted using NOAA meteorological stations, yielding satisfactory accuracy levels.

Table 1. DSR product characteristics (NOAA NESDIS, 2018)

Name	User & Priority	Geographic Coverage	Horizontal Resolution	Measurement Range	Refresh Rate/Coverage
Downward Solar Insolation: surface	GOES-R	Conus	25 km	0 – 1500 W/m^2	60 min

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With the values of DSR we use the Ridley and Boland model to determine the DNI (Ridley et al., 2010). To assess the exergy potential of solar radiation, we apply a generalized model based on a photo-thermal work extractor (Fig. 2). This extractor operates in conjunction with a high-temperature radiation reservoir through an absorber and a low-temperature heat sink via a cooler, as detailed by González-Mora et al. (2023). The absorber captures incoming solar radiation (φ_{H}), but to maintain thermal equilibrium, it must also emit thermal radiation (φ_{a}). The difference between the absorbed and emitted radiation generates work ($\dot{W}$) while rejecting heat to the environment ($\dot{Q}_{out}$).

To evaluate the maximum available exergy value, we first determine the optimal absorber temperature (T_a) for each concentrator by solving Eq. (1a). This determination requires knowledge of the reference environment's temperature (T_L), thermal conductance (λ_c), the Stefan-Boltzmann constant (σ) and the Concentration-Acceptance Product (f_H), as detailed by González-Mora et al. (2023). Subsequently, we evaluate the maximum efficiency conversion using Eq. (1b). By incorporating the direct normal radiation value (DNI), we derive the exergy value of solar radiation using Eq. 1c. This structured approach ensures a systematic and accurate assessment of the solar exergy potential, providing a robust foundation for comprehensive analysis within the study's framework.

$$4\sigma^2 T_a^{11} - 8\sigma\lambda_c T_a^8 - 8\sigma^2 f_H T_H^4 T_a^7 + 4\lambda_c^2 T_a^5 - T_a^4(3T_L\lambda_c^2 - 8\lambda_c\sigma f_H T_H^4) + 4T_a^3\sigma^2 f_H^2 T_H^8 - \lambda_c^2 T_L f_H T_H^4 = 0 \tag{1a}$$

$$\eta = \left(1 - \frac{1}{f_H}\left[\frac{T_a}{T_H}\right]^4\right)\left(1 - \frac{\lambda_c T_L}{\lambda_c T_a + \sigma\left(f_H T_H^4 - T_a^4\right)}\right) \tag{1b}$$

$$\dot{Ex}_{G_{bn}} = DNI\eta \tag{1c}$$

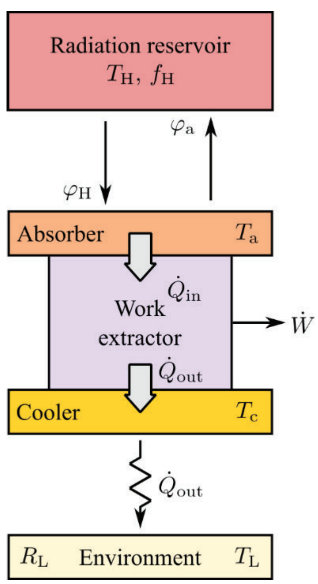

Figure 2: Photo-thermal work extractor in contact with heat and radiation reservoirs. Adapted from (González-Mora et al., 2023).

In assessing the group of equations (Eqs. 1), we rely on the values outlined in Table 2. We have standardized the reference temperature (T_L) under standard conditions, emphasizing its fixed nature. This standardization is integral for a consistent and accurate exergy analysis, as noted by Szargut (2005),

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and provides a foundation for understanding the efficiency of solar radiation conversion processes. We consider the Sun's temperature (T_H) fixed, treating it as a black body radiation source. Following Kakaç's (2012) recommendations, we have selected a typical thermal conductance value for the cooler (λ_c), applicable to power systems. Given our focus on determining the maximum exergy potential of solar radiation, we set the concentration acceptance product (f_H) to its maximum value of 1. It is important to note that for specific concentrator systems, such as parabolic collectors and solar towers, the concentration acceptance product is inherently less than one due to limited light acceptance within a defined angle. This methodological approach ensures a thorough and precise evaluation of the solar radiation exergy potential, contributing to a nuanced understanding of the studied processes.

Table 2: Solar exergy analysis considered values.

Parameter	Value
T_L	300 K
T_H	5777 K
λ_c	25 kW/m^2·K
f_H	1

3 RESULTS

For this study, the solar radiation data were determined from the GOES-DSR product corresponding to hourly horizontal irradiance (W/m^2) for Mexico's different months and climate conditions. For reference, we consider the month with the maximum insolation, July 2023, and the month with the lowest radiation conditions, December 2022. With these data, we determine the DNI and the exergy radiation by applying the methodology described in section 2.

In Fig. 3 (a) and (b), the maximum hourly horizontal irradiance and DNI for July 2023 are shown, while the exergy radiation for this period is shown in Fig. 4.

This exergy potential would correspond to the maximum useful energy that could be obtained in that month with a solar concentrator with a concentration acceptance product of 1. In the analyzed maps, it can be seen that, although it is true that the maximum irradiance in July can reach values of 1032.93 W/m^2. The maximum exergy value would be 790.6 W/m^2, corresponding to a DNI of 865.44 W/m^2. This maximum value is located in San Francisco Borja Chihuahua, Mexico (27.87º N, 106.87º W).

Likewise, in Figs. 5 and 6, the irradiance and DNI for December 2022 and its correspondence exergy radiation are shown. It can be observed that for this period of time the maximum exergy radiation is 440W/m^2. This value is almost half of the maximum exergy obtained in July 2023.

These exergy values represent a useful index in the preliminary assessment of the performance of solar technologies since the model provides the upper limit of the system's efficiency. Considering the irreversibilities generated in both the high-temperature radiation reservoir and a low-temperature heat sink. It is crucial to emphasize that the maps depicted in Figs. 2-5 represent the theoretical maximum exergy potential achievable with a solar concentrator, denoted as $f_H = 1$. This scenario assumes that the Sun illuminates the entire hemisphere from the radiation source to the absorber. For varied concentrator designs, it is necessary to identify the appropriate f_H value, thereby enabling the creation of specific concentration exergy maps tailored to each geometry.

In the context of commercial large-scale parabolic collectors utilized in CSP, such as Eurotrough, LS-3, and ASTRO, among others, f_H is approximately 5.674×10^{-4}. For small-scale parabolic collectors for SHIP, including models like Power Trough 110, Power Trough 250, PTC-1100, and PTC950 f_H ranges between approximately 2.271×10^{-4} and 4.309×10^{-4}.

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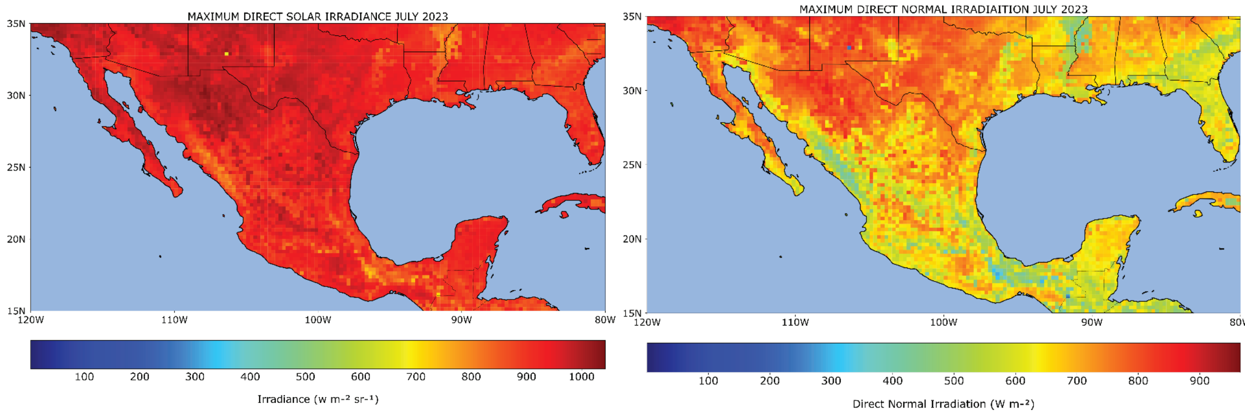


a) b)

Figure 3: July 2023 a) Maximum global solar irradiance (DRS) W m^{-2}, b) Maximum direct solar irradiance W m^{-2}

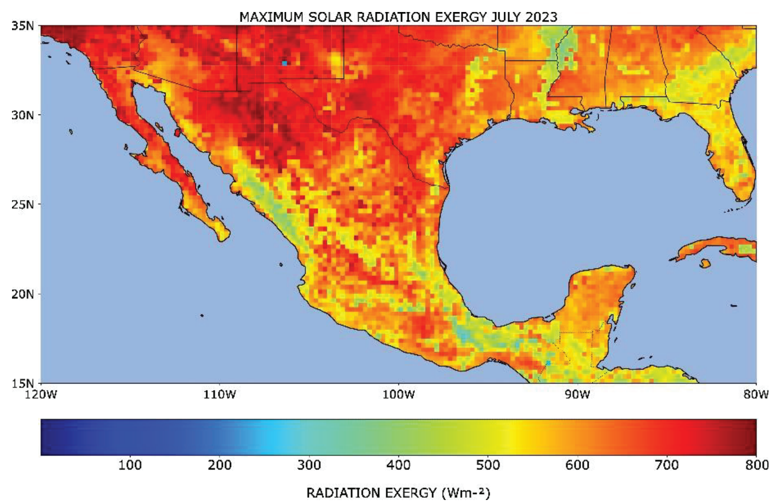
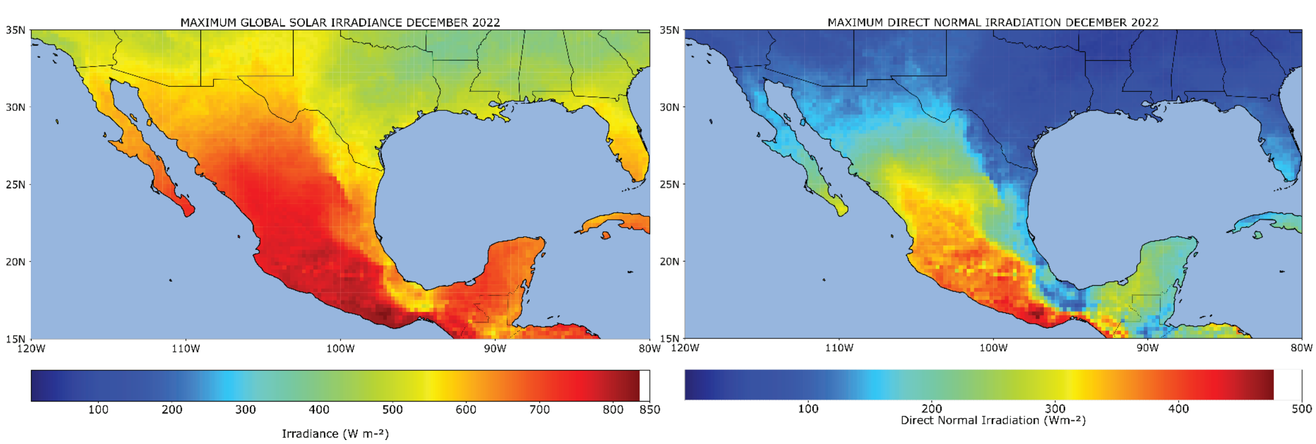


Figure 4: Maximum solar radiation exergy July 2023 W m^{-2}



a) b)

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Figure 5: December 2023 a) Maximum global solar irradiance (DRS) W m^{-2}, b) Maximum direct solar irradiance W m-2

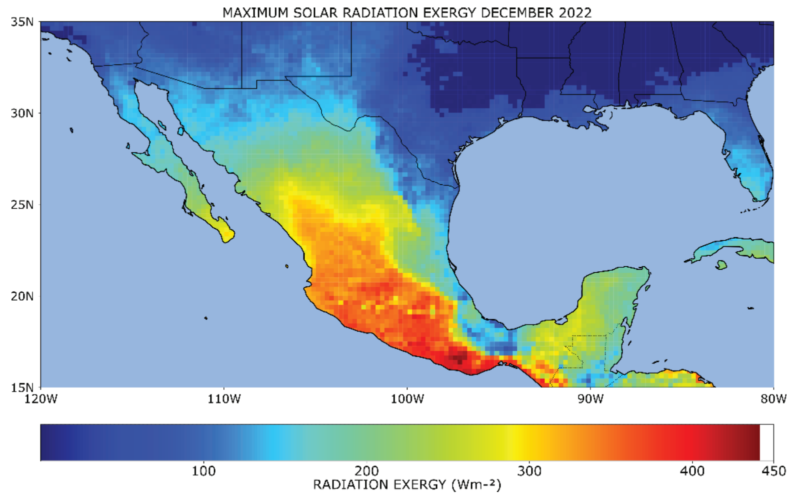

Figure 6: Maximum solar radiation exergy Dec 2023 W m^{-2}

Regarding solar tower technologies exemplified by projects such as PS10, PS20, Gemasolar, Ivanpah, and Cerro Dominador, f_H values lie within the range of approximately 0.2166 to 3.249×10^{-2} (Vant-Hull, 2021). Advanced tower systems, such as the one employed in the SUN-to-LIQUID project (Romero et al., 2017), exhibit an f_H of approximately 5.415×10^{-2}, whereas the Bigdish parabolic dish system has an f_H of approximately 4.594×10^{-2} (Lovegrove et al., 2011). These specific f_H values illustrate the nuanced potential of diverse solar concentrator geometries in harnessing solar exergy.

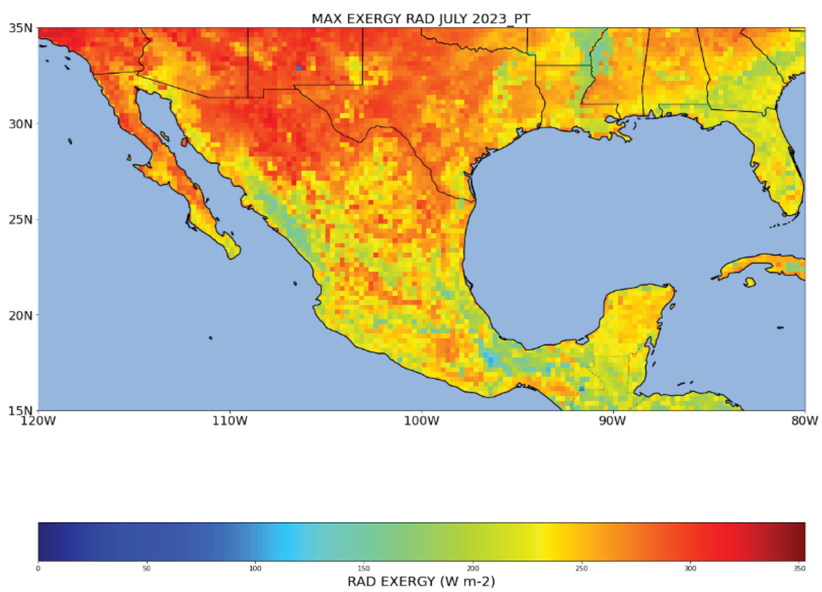

Figure 7: Maximum solar radiation exergy, PTC950, July 2023 W m^{-2}

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To contextualize our analysis, we shall calculate the radiation exergy utilizing the f_H value of a commercial concentrator, specifically the PTC950 parabolic trough collector. Considering an f_H value of 4.309×10^{-4} we derive the map of maximum exergy for July 2023 (Fig. 7). The results indicate that the peak radiation exergy value is 350 W/m^2, representing the maximum obtainable useful energy with this technology under the specified conditions. This value highlights the real potential of the PTC950, offering a benchmark for future advancements in solar energy conversion. By understanding these metrics, we can better gauge the performance and applicability of parabolic trough collectors in various climatic conditions,

Now, to enhance clarity regarding the findings presented in this paper, a specific representative location, Agua Prieta, Sonora (31°19′ N, 109°32′ W, 1219 m), was carefully chosen. The selection of this particular site was predicated upon the presence of an integrated solar combined cycle (ISCC) power plant constructed by Abengoa in 2014. This facility, equipped with parabolic trough collectors, boasted a nominal power capacity of 12 MW, rendering it a noteworthy landmark as the sole Concentrated Solar Power (CSP) plant in Mexico.

Subsequently, a comprehensive analysis was conducted at this specific locale to determine the maximum radiation exergy for each month. The outcomes of this analysis are delineated in Fig. 8, providing insights into the maximum available energy potential throughout 2023 at Agua Prieta.

Additionally, Figure 9 delineates, for the specific location of Agua Prieta, the disparities among Downward Shortwave Irradiation (DSR), Direct Normal Irradiance (DNI), and exergy values for the day characterized by the highest insolation in 2023. Also, in this graphic it is included the calculation of solar exergy considering the concentration acceptance product of 4.309×10^{-4}. Within this graphical representation, the area beneath the green curve symbolizes the pinnacle of usable energy attainable at the specified location during that time frame. This visualization underscores the significant variation in energy capture and conversion efficiency throughout the day, providing critical insights into optimizing solar energy utilization at Agua Prieta, and easily extrapolated to other mexican locations.

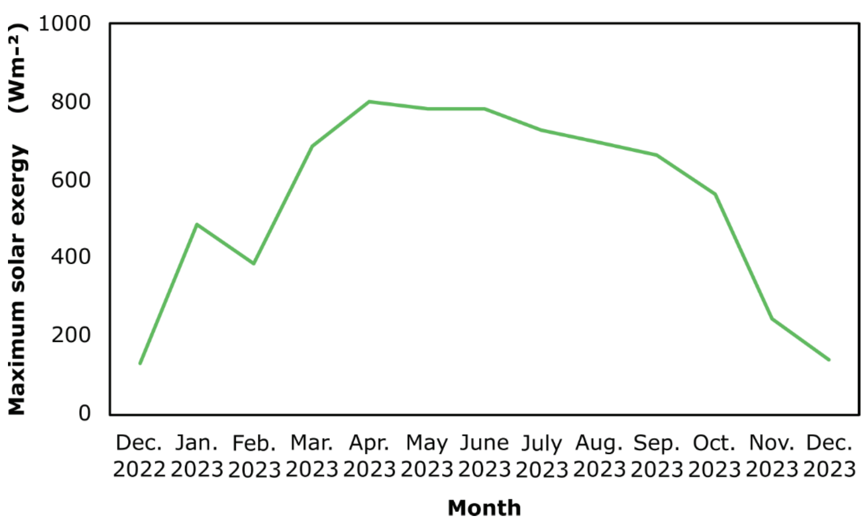

Figure 8: Maximum radiation exergy for each month in Agua Prieta, Sonora.

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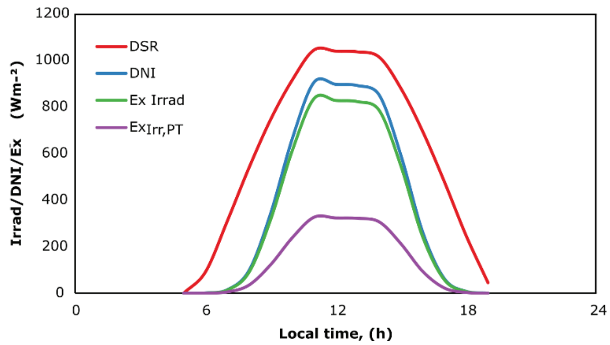

Figure 9: DSR, DNI, and radiation exergy for the day with the maximum insolation in 2023 in Agua Prieta, Sonora.

4 CONCLUSIONS

In this study, we have meticulously analyzed both Direct Normal Irradiance (DNI) and radiation exergy maps for Mexico. Our investigation leads to several insightful conclusions that could significantly influence the design and implementation of solar thermal and Photovoltaic (PV) systems within the region.

Firstly, we discovered that the DSR product stands out as a valuable tool for estimating the potential of global solar radiation—encompassing both direct and diffuse components—in Mexico. This estimation is crucial for accurately dimensioning solar thermal and PV systems, addressing the country's critical need for more precise radiation information.

Currently, innovative systems and databases, such as the PVGIS (2022) web interface, facilitate the calculation of solar radiation and photovoltaic (PV) system energy production, serving as powerful tools for estimating PV potential within the European Union. However, Mexico lacks similar freely accessible tools; the available options, such as SOLCAST (2024) and Meteonorm (2020), require payment. Furthermore, this article focuses on the potential of solar concentration systems, particularly in determining the maximum energy available for a given concentration technology based on irradiation and temperature conditions derived from satellite data. Comparable studies for the Mexican region are notably absent.

Our analysis further indicates that relying solely on global radiation or Direct Normal Irradiance (DNI) can result in overly optimistic projections of energy yields from solar concentrators. Thus, utilizing radiation exergy as a more realistic analytical tool is crucial. The development of radiation exergy maps is especially effective for understanding the performance of solar thermal systems under specific climatic conditions and for identifying opportunities to enhance existing systems.

These radiation exergy maps have broad potential applications, extending beyond the current study to create exergy landscapes for various locations throughout Mexico and potentially across North America. Such an expansion would significantly enrich the dataset available to researchers and industry professionals, fostering advancements in solar energy utilization.

Our proposed methodology demonstrates a keen ability to accommodate the diverse f_H values characteristic of different solar concentrator technologies. By enabling the generation of customized exergy maps, this approach promises to refine the design and application of concentrator systems across the spectrum of Concentrated Solar Power (CSP) projects.

Looking ahead, we plan to refine our model further by incorporating air temperature data obtained via satellite. This enhancement is expected to yield even more precise estimates of radiation exergy, thereby advancing solar energy research and application. Our ongoing work underscores a commitment to

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improving the efficiency and viability of solar energy systems, focusing on Mexico's unique environmental and technological context and, by extension, North America.

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