

SYNERGISTIC WATER-ENERGY MANAGEMENT: PHOTOVOLTAIC CANAL COVERS FOR CLIMATE RESILIENCE IN ARID REGIONS

GESTION SYNERGIQUE EAU-ÉNERGIE : COUVERTURES PHOTOVOLTAÏQUES DE CANAUX POUR LA RÉSISTANCE CLIMATIQUE DANS LES RÉGIONS ARIDES

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ABSTRACT

Arid and semi-arid regions, such as Iran, face serious water resource management challenges exacerbated by climate change, which threaten agricultural resilience. Evaporation loss from open irrigation canals is a primary cause of water depletion. This research evaluates an innovative, dual-purpose technology of covering irrigation canals with photovoltaic (PV) systems, which simultaneously generates renewable energy and reduces evaporation losses. The primary objective is to quantify the synergistic benefits of this system and present a justifiable and scalable economic model for the sustainability of irrigation infrastructure. This case study focuses on a 500-square-meter section of the right bank canal of the Nowruzlu Diversion Dam in Miandoab. The methodology involves utilizing Meteonorm software to extract climate data and verify the temperature increase trend, and PVsyst software to simulate system performance and determine the optimal panel tilt angle, alongside a comprehensive economic analysis based on the tariffs of the year 1404. Findings indicate that the optimal tilt angle of 37 degrees, resulting in 67% coverage of the canal surface, can generate approximately 131 MWh of electricity annually. Concurrently, the shading effect of the panels reduces evaporation by up to 55%, equivalent to an annual water saving of 257.3 cubic meters. Economic analysis reveals that with an initial investment of 25 billion Rials, the combined revenue from electricity sales and water savings yields a net annual profit of 2.346 billion Rials, resulting in a payback period of 10.66 years. Assuming a useful life of 25 years, the annual return on investment (ROI) is estimated at 9.4%. Ultimately, this strategic solution transforms water conveyance canals into dynamic assets and strengthens the Water-Energy Nexus, serving as a replicable model for policymakers to achieve Sustainable Development Goals.

Keywords: Irrigation canal, Photovoltaic systems, Solar energy, Sustainable development, Reducing water evaporation losses, Water-energy nexus.

RESUME

Les régions arides et semi-arides, comme l'Iran, sont confrontées à des défis majeurs en matière de gestion des ressources en eau, exacerbés par le changement climatique, qui menacent la résilience agricole. La perte par évaporation au niveau des canaux d'irrigation à ciel ouvert est une cause principale de l'épuisement de l'eau. Cette recherche évalue une technologie innovante à double usage de couverture des canaux d'irrigation avec des systèmes photovoltaïques (PV), permettant simultanément de produire l'énergie renouvelable et de réduire les pertes par évaporation. L'objectif principal est de quantifier les avantages synergiques de ce système et de présenter un modèle économique justifiable et évolutif pour la durabilité des infrastructures d'irrigation. Cette étude de cas se concentre sur une section de 500 mètres carrés du canal de la rive droite du barrage de dérivation de Nowruzlu à Miandoab. La méthodologie implique l'utilisation du logiciel Meteonorm pour extraire les données climatiques et vérifier la tendance de la hausse des températures, et le logiciel PVsyst pour

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simuler les performances du système et déterminer l'angle d'inclinaison optimal du panneau. Les résultats indiquent que l'angle d'inclinaison optimal de 37 degrés, qui permet une couverture de 67% de la surface du canal, peut générer environ 131 MWh d'électricité par an. Simultanément, l'effet d'ombrage des panneaux réduit l'évaporation jusqu'à 55%, ce qui équivaut à une économie d'eau annuelle de 257,3 mètres cubes. L'analyse économique révèle qu'avec un investissement initial de 25 milliards de rials, le revenu combiné issu des ventes d'électricité et des économies d'eau produit un bénéfice annuel net de 2,346 milliards de rials, ce qui donne une période de retour de 10,66 ans. En supposant une durée de vie utile étant 25 ans, le retour sur investissement annuel (ROI) est estimé à 9,4%. En fin de compte, cette solution stratégique transforme les canaux de transport d'eau en actifs dynamiques et renforce le lien entre eau-énergie, constituant un modèle qui peut être reproduit pour les décideurs politiques afin d'atteindre les objectifs de développement durable.

Mots-clés : Canal d'irrigation; Systèmes photovoltaïques; Énergie solaire; Développement durable; Réduction des pertes d'eau par évaporation; Liens entre eau-énergie.

INTRODUCTION

Water, as the most fundamental element of life, plays a key role in sustainable development, public health, and food and economic security. Although water covers more than 70% of the Earth's surface, less than 1% of the world's water resources are available for human uses, including drinking, agriculture, and industry (Babu et al., 2010). Meanwhile, a worrying trend of population growth, intensifying pollution, urbanization expansion, and the increasing effects of climate change has exerted unprecedented pressure on limited water resources (Piri et al., 2009).

The amount of water available on planet Earth is almost always constant. In terms of volume, more than 87% of the water on Earth is accumulated in oceans and seas, and about 6% is accumulated as ice and glaciers in polar regions, with only 1% of the world's water available for direct use. This 1% is found in rivers, lakes, atmospheric moisture, soil moisture, and groundwater (Alizadeh, 2006).

The average annual rainfall globally is about 850 mm, while in Iran it is only 250 mm, indicating the limitation of renewable water resources in the country. Examining the spatial and temporal distribution of precipitation also indicates a severe imbalance in the distribution of atmospheric precipitation; so that 70% of the country's rainfall occurs in only 25% of its area, and about 75% of the precipitation falls at a time when agricultural water demand is minimal. These conditions further reveal the necessity of optimal water utilization. Meanwhile, millions of cubic meters of freshwater, stored at significant cost in dams and lakes, are lost annually through evaporation. This loss of water resources, especially in arid countries like Iran, is among the serious challenges in water resource management. In addition to the quantitative reduction of water, the increase in the concentration of salts and minerals following evaporation leads to a decline in water quality, and consequently, soil degradation and reduced agricultural productivity (Nematollahi et al., 2015). These conditions have doubled the need for precise planning and management of water resources (Piri et al., 2009).

Therefore, one of the fundamental challenges in water resource management, especially in arid and semi-arid regions like Iran, is the phenomenon of evaporation. On average, globally, about 57% of atmospheric precipitation evaporates immediately, and this amount is considerably higher in Iran due to the intensity of solar radiation, heat, and wind (Alizadeh, 2012). A significant portion of the water stored behind dams, in pools, and in irrigation canals is lost solely through evaporation without being utilized. According to estimates, over 10 billion cubic meters of water stored behind dams in Iran evaporates annually (Soltani et al., 2018).

Reduced precipitation due to climate change has caused numerous consequences worldwide, especially in arid and semi-arid regions. Over recent decades, the increase in pollutants, fossil fuel consumption (mainly in underdeveloped and developing countries), land-use changes, and vegetation depletion have gradually exacerbated the negative effects of climate change, subsequently leading to a water crisis as one of the fundamental problems. Reduced rainfall and recurrent droughts, followed by

a decline in surface water levels, have led to further exploitation of groundwater resources, resulting in severe depletion of groundwater in many areas due to over-extraction. To curb this situation, it is necessary to identify and control the main factors increasing the negative effects of these changes, including evaporation (Poshtkouhizadeh, 2015; Mazaheri and Koupai, 2018). Failure to properly manage these conditions, in addition to increasing the concentration of salts and reducing the quality of water resources, also leads to soil degradation and reduced efficiency in irrigation networks.

By the late 20th century, about 45,000 large dams had been constructed worldwide, with the total surface area of their reservoirs exceeding 500,000 square kilometers. The primary purpose of constructing these dams was to store water to meet various needs such as agricultural irrigation, hydroelectric power generation, and supplying drinking water to covered areas. However, one of the fundamental challenges that emerged after the construction of these hydraulic structures is surface evaporation and the noticeable reduction of water reserves in reservoirs. Evaporation, as one of the key components in the hydrological cycle, can lead to the loss of a significant portion of precipitation, especially in arid climates, and severely reduce the efficiency of storage in dams (Soltani et al., 2018). The importance of evaporation in the hydrological cycle becomes evident when recalling that on a global scale, about 57% of the water falling on land as atmospheric precipitation evaporates directly. The amount of evaporation from seas is 110% of the atmospheric precipitation on them. This means more water evaporates from the sea surface than falls as rainfall on them. In arid and semi-arid climates like Iran, the vast majority of annual precipitation enters the atmosphere through evaporation immediately after rainfall (Alizadeh, 2012).

Water evaporation is a process that depends on wind speed and the moisture gradient between the water surface and the atmosphere above. The moisture gradient is determined by air dryness and temperature (Helfer et al., 2009), and among these, solar radiation plays a very prominent role. Iran, with an average of 12 hours of daily sunshine in many regions, is considered one of the most susceptible countries to high evaporation rates (Nematollahi et al., 2015). Although scientific literature suggests solutions such as physical, chemical, and biological covers to control evaporation, extensive and effective practical measures have not been taken in this regard in the country (Farzin and Alizadeh, 2015).

In many developed countries, a combination of physical, chemical, and biological methods is used to reduce evaporation from surface water resources and soil. These measures include the use of worn tires, windbreaks, white and black floating balls, lightweight perlite concrete floating panels, fatty alcohols such as hexadecanol and octadecanol, cover plants like duckweed, water demand management, water recycling, water surface covering materials, and reforming water allocation policies (Alvarez et al., 2006; Helfer et al., 2009; Soltani et al., 2018; Sepaskhah, 2018; Rezazadeh et al., 2020). Among chemical methods, the use of monomolecular fatty alcohols, which sit on the water surface and prevent evaporation, has been reported effective. Due to their molecular structure, these substances form a thin, invisible layer with a thickness of less than a nanometer that reduces evaporation. In Australia, the use of hexadecanol led to about a 20% reduction in evaporation, while this substance did not have significant effectiveness in the USA (Piri et al., 2009; Sepaskhah, 2018). Also, the use of steerol alcohols in North Africa and the United States has shown a significant reduction in evaporation and greater efficiency compared to physical methods like windbreaks, provided they are applied regularly. In biological methods, the use of live and dead duckweed to cover the water surface has been tested. Results have shown that live plants reduce evaporation compared to dead cover and no cover, and aeration also significantly reduces surface evaporation (about 13.79%). The performance difference between live and dead plants reached about 5.57% after two weeks, and this difference is greater in the real environment (open air) than in the laboratory (Soltani et al., 2018).

In the field of physical covers, various experiments have been conducted in different countries. In Spain, black polyethylene covers in single and double layers in a Class A evaporation pan resulted in 75% and 83% evaporation reduction, respectively (Alvarez et al., 2006). In Egypt, the use of circular ringed foam sheets with 82.7% surface coverage resulted in a 74% reduction in evaporation (Hassan et al., 2007). In Iran, research was conducted using white and black floating balls, which showed that the least

evaporation occurs when using white balls. The combination of black and white balls was also effective in reducing evaporation, but the sole use of black balls had lower performance (Rezazadeh et al., 2020). In another project at the Sarcheshmeh Copper Complex, a physical Unoring cover using designed rubber rings was used in two test basins. This cover resulted in a 78.35% reduction in evaporation (Afkhami et al., 2017). Also, lightweight perlite concrete floating panels were used at the Karun Dam. These panels, made of polypropylene, were designed to be hollow and connectable, and were effective in reducing direct solar radiation and consequently evaporation (Sepaskhah, 2018).

Another type of cover is modular floating covers, which are placed on the water surface and reduce evaporation by reflecting part of the solar radiation. These covers are mostly designed for small water resources and have been rarely tested on large reservoirs. Due to gaps between the modules, these covers allow the exchange of dissolved oxygen between the air and water (Yao et al., 2010).

A numerical study of surface water evaporation in India by Joshi et al. (2021) showed that the use of chemical methods such as cetyl alcohol and steerol alcohol leads to a 20 to 40 percent reduction in evaporation, and planting windbreak trees is also 15 to 25 percent effective. Overall, floating covers have the greatest impact with about a 70 percent reduction in evaporation. This study emphasizes that the use of methods that simultaneously produce energy while reducing evaporation will have greater effectiveness and efficiency.

Regarding energy generation, the sun's energy can be considered a massive natural nuclear reactor in which matter is converted into energy through the nuclear fusion process. In this process, about 350 billion tons of the sun's mass is converted into electromagnetic radiation daily. The temperature of the sun's core is about 15 million degrees Celsius, and the resulting energy reaches the Earth as visible, infrared, and ultraviolet rays; so that the amount of energy received at the Earth's surface is estimated at about one kilowatt per square meter. Part of this energy (nearly one-third) is scattered in space along the way, and the rest reaches the Earth. Estimates show that the amount of solar radiation energy reaching the Earth is about 10,000 times greater than the current total energy consumption of humanity. Based on predictions, human energy consumption will increase by 50 to 300 percent by 2050. Under these conditions, if only 0.1 percent of the Earth's surface were allocated to solar energy converters with an efficiency of about 10 percent, it would be possible to meet all of humanity's energy needs (Azad, 1984).

To capture solar energy, a system known as photovoltaic cells is used. These systems include panels that are utilized to control evaporation from water resources as well as to generate renewable electricity. The direct conversion of solar radiant energy into electricity is mainly done through photovoltaic cells, which are based on the physical phenomenon of the photovoltaic effect. This effect arises from the interaction of photons with energy equal to or greater than the bandgap energy of photovoltaic materials with the cell surface.

Photovoltaic modules convert solar energy into electrical current without creating pollution, noise, or grid fluctuations. Since the energy density of solar radiation is relatively low, a vast area of solar panels will be required to produce a meaningful amount of electrical energy. In grid-connected photovoltaic systems, inverters are used to convert the direct current (DC) generated by solar arrays into alternating current (AC) consistent with the grid's voltage and frequency (Niroo Research Institute, 2014).

One of the most innovative solutions is the use of floating solar panels on storage reservoirs (Patil et al., 2017). A solution that not only reduces evaporation but also provides clean and renewable energy generation.

Despite the development of related technologies, the use of solar energy in the country remains very limited. Based on the aforementioned, one of the major issues in the country is severe water evaporation; evaporation in regions with arid and semi-arid climatic conditions like Iran, which has also faced the problem of water crisis in recent years, also causes a decrease in the quality of surface and groundwater resources. As evaporation increases, the concentration of salts and minerals in water rises,

and in addition to declining water resource quality, it leads to soil degradation and subsequently further problems such as reduced crop quality and even soil erosion. Therefore, controlling evaporation can be highly effective in managing such critical conditions and the occurrence of subsequent severe effects, which requires technological measures to address.

In this regard, Raouf and Rezaei (2017) conducted a feasibility study on the use of solar panels to reduce evaporation and simultaneously generate electricity at the Shahid Kazemi Dam, showing that this method recovers its initial costs within 6 years.

Also, Rezaei and Ahmadi (2021), by conducting an economic analysis of installing solar panels on the lake of the Nowruzlu Diversion Dam, achieved the optimal panel placement angle in terms of radiation reception and evaporation reduction.

Consequently, the application of surface covers as a practical solution for reducing water evaporation from surfaces has been confirmed. However, limited research has been conducted regarding the performance of energy-generating and evaporation-reducing solar panels on the surface of irrigation canals in the country. Therefore, this study investigates the existing evaporation and energy potential in the region and examines the feasibility of employing solar panels as a strategy to control and conserve water from evaporation, as well as to produce clean energy in the Right Bank conveyance canal downstream of the Nowruzlu Diversion Dam.

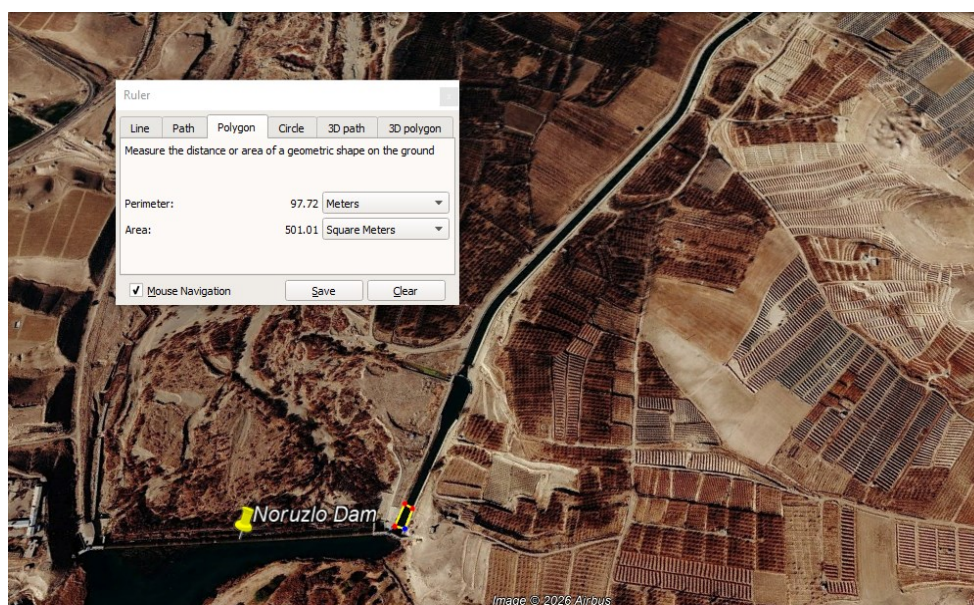


Figure 1. Aerial photo of the right bank channel downstream of the Nowruzloo diversion dam

STUDY AREA

The study area in this research is the conveyance canal branching from the Nowruzlu Diversion Dam, located on the right bank of the Zarrineh-Rud River in West Azerbaijan Province, with geographical coordinates of 36.8° N and 46.2° E, 15 kilometers south of Miandoab County. The average precipitation and temperature of the study area are 158 mm and 5.5 °C, respectively, and based on the De Martonne method, this basin has a semi-arid climate. The study area encompasses rainfed and irrigated agricultural lands, rangelands, orchards, bare lands, residential areas, and rocky lands within the Miandoab County region. This case study focuses on a 500-square-meter section of the right bank canal of the Nowruzlu Diversion Dam in Miandoab. The location of the study basin is presented in Figure 1.

METHODOLOGY

Meteonorm Software

Meteonorm software is a unique combination of reliable data sources and sophisticated calculation tools that provide access to typical meteorological years and recorded time series. This software is used to generate climate data for many cities and locations worldwide. A persistent problem in energy simulations, where local weather information is involved, is the lack of extensive climate data (especially daily and hourly) (Remund et al., 2010).

PVsyst Software

In this software, comprehensive calculations of solar photovoltaic systems and the simulation of grid-connected, stand-alone, and solar pumping systems, shade effect analysis, importing meteorological data from various sources as well as personal data (manually), and their subsequent analysis and reporting are possible (Khammar et al., 2020).

RESULTS AND DISCUSSION

In this study, the Meteo model outputs related to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) were utilized. These outputs were interpolated and extracted from the IPCC website based on data published from adjacent stations (Urmia, Tabriz, Maragheh, Zanjan, and Sarab) in the region under RCP 2.6, RCP 4.5, and RCP 8.5 scenarios. By observing the extracted software results for the year 2020 and comparing the 10-year predictions of the scenarios, a gradual increase in the temperature parameter is evident, while the energy potential remains similar to the present or experiences a decline. This subsequently reveals the gradual increase in global warming, which is not unexpected due to reasons such as climate change and increased pollution; this can be observed in Figures 2 to 9.

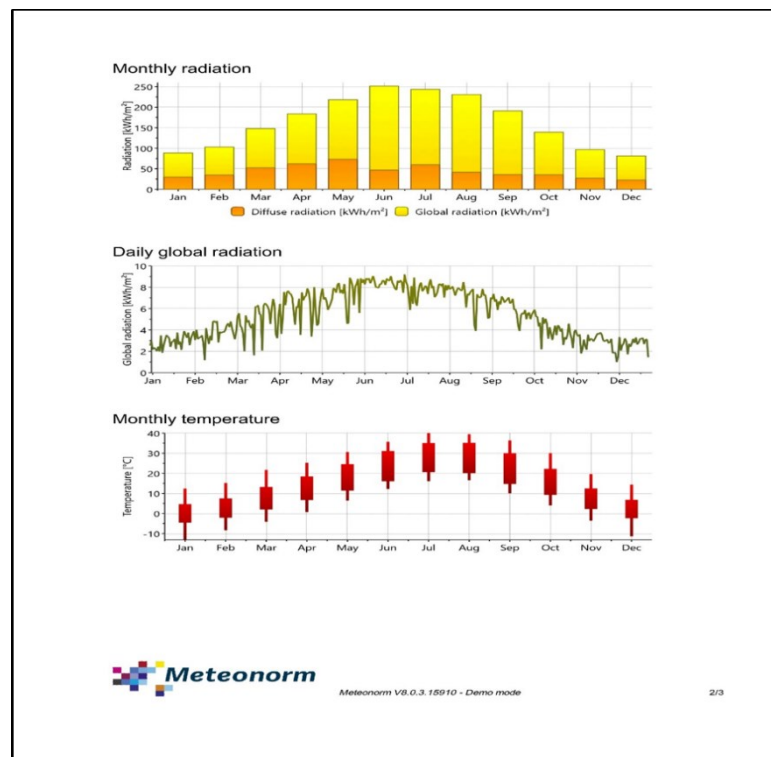


Figure 2. Meteonorm software extracted results for the year 2020

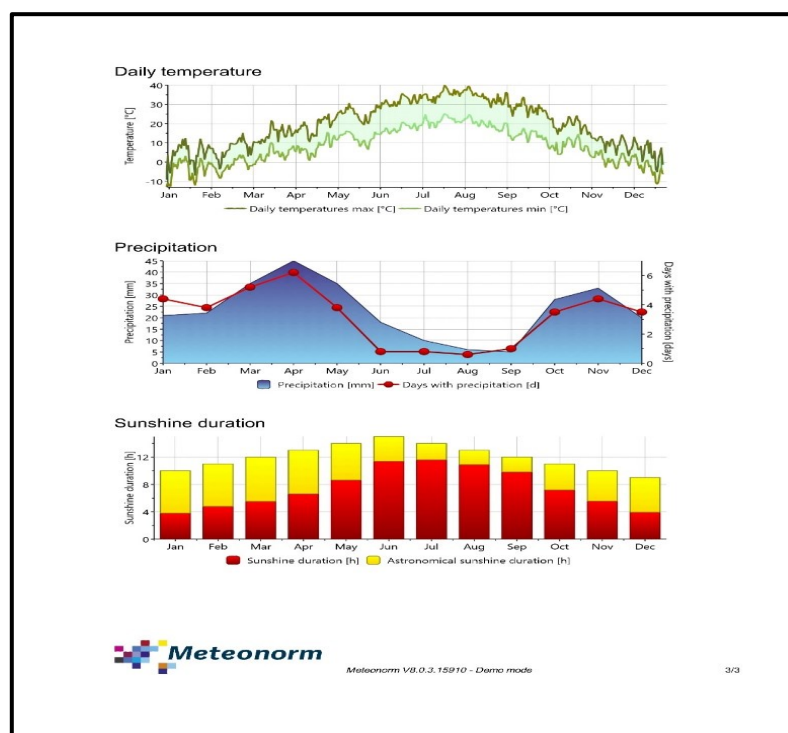


Figure 3. Meteonorm software extracted results for the year 2020

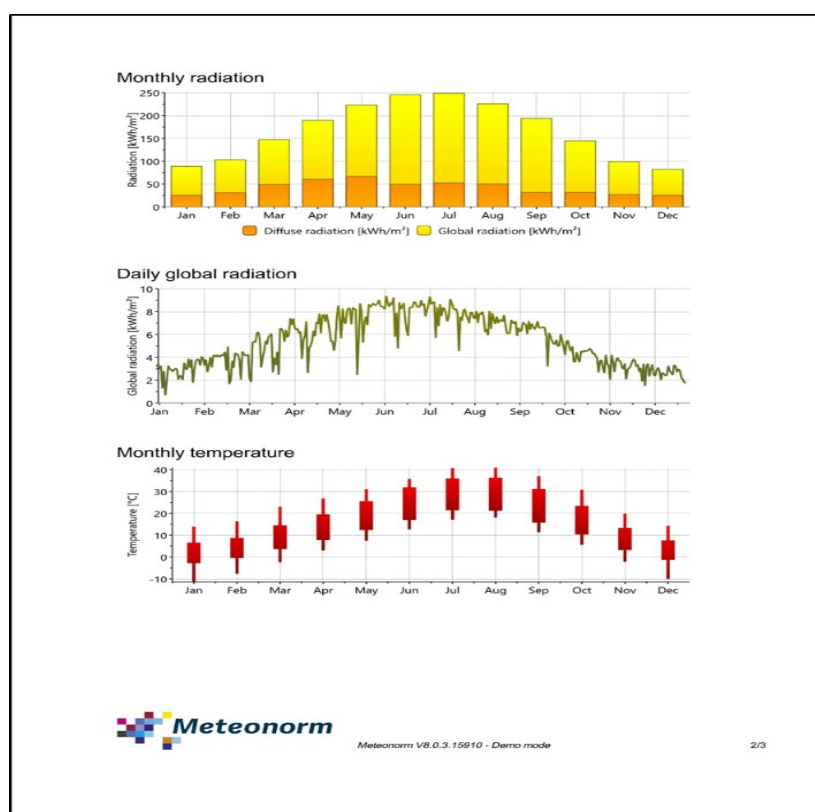


Figure 4. Meteonorm software prediction results for RCP 2.6 scenario in the year 2030

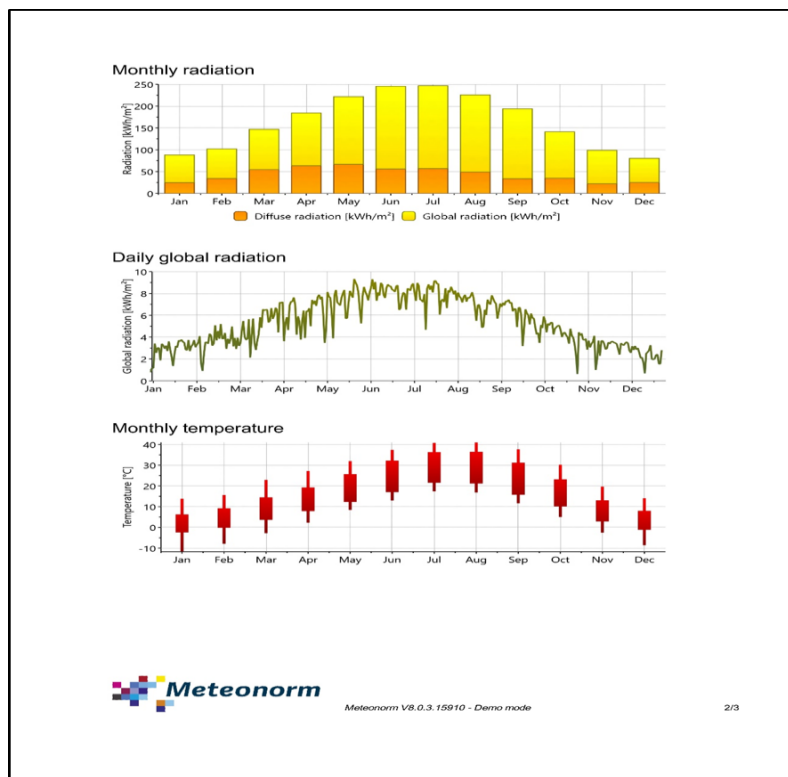


Figure 5. Meteonorm software prediction results for RCP 2.6 scenario in the year 2030

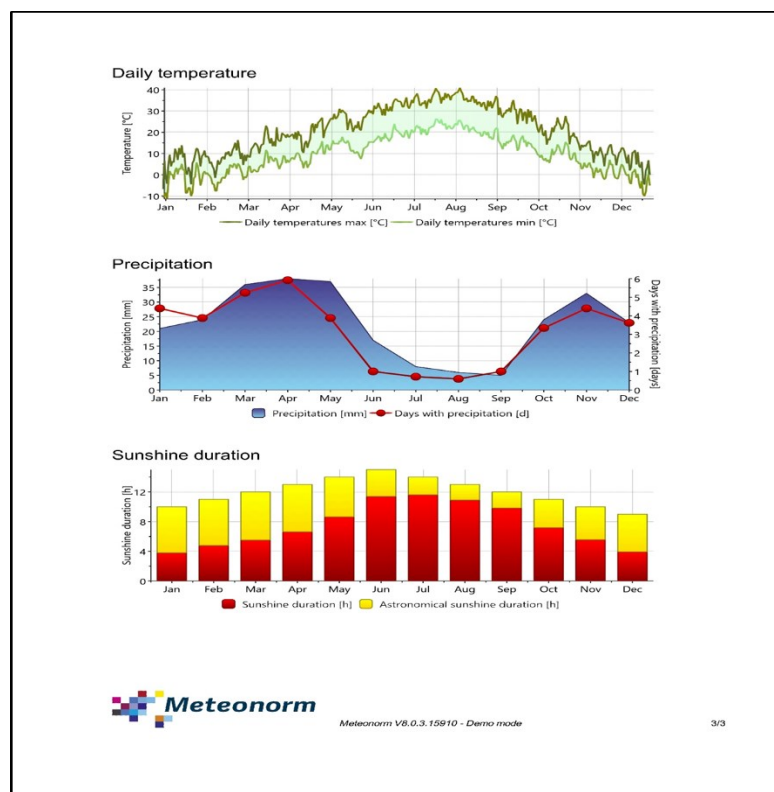


Figure 6. Meteonorm software prediction results for RCP 4.5 scenario in the year 2030

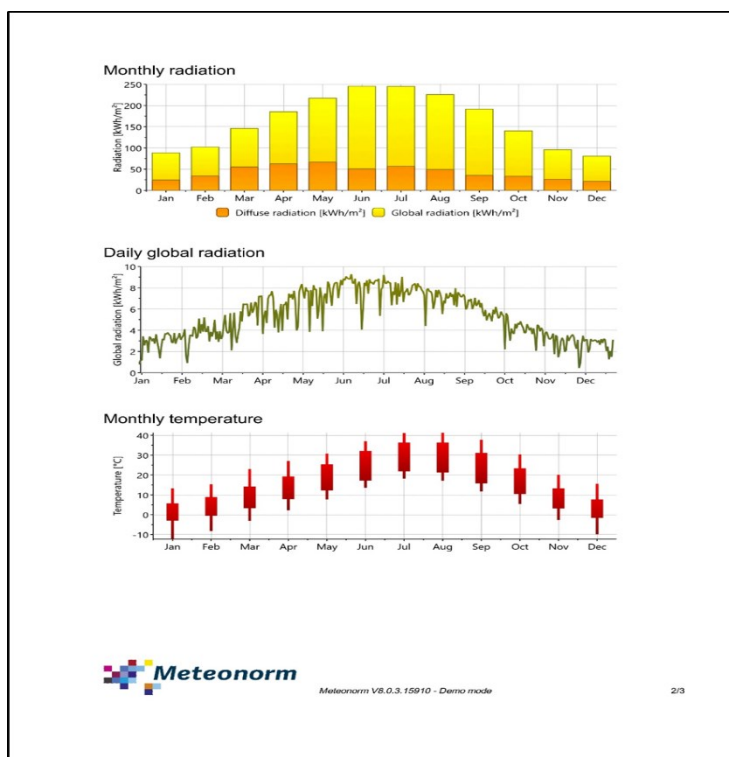


Figure 7. Meteonorm software prediction results for RCP 4.5 scenario in the year 2030

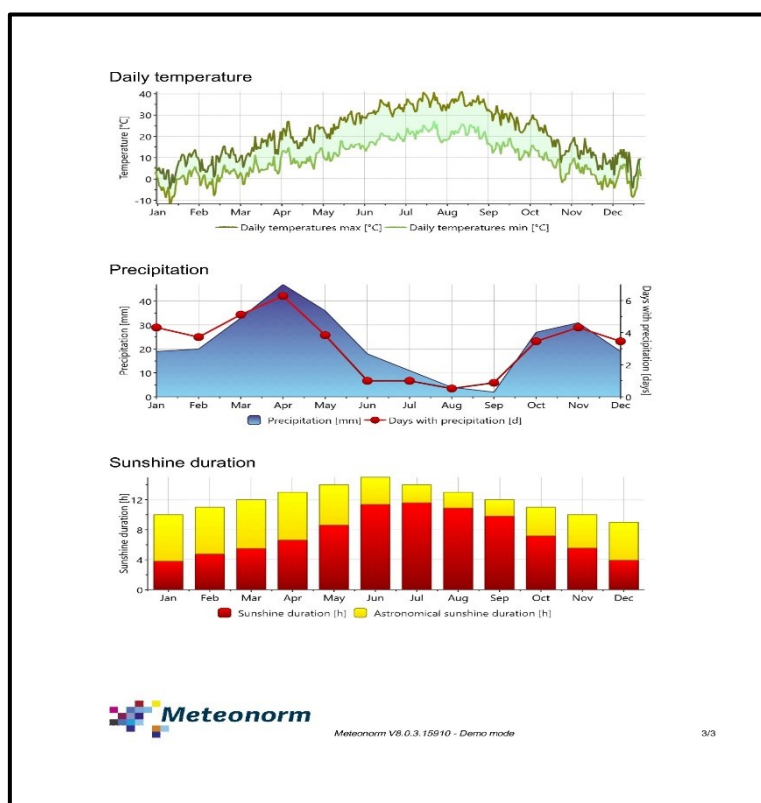


Figure 8. Meteonorm software prediction results for RCP 8.5 scenario in the year 2030

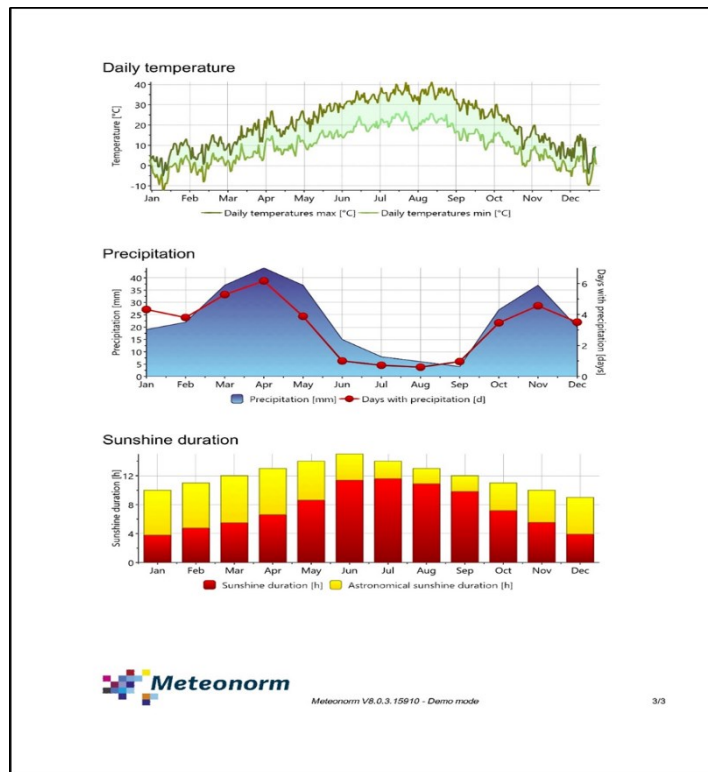


Figure 9. Meteonorm software prediction results for RCP 8.5 scenario in the year 2030

Based on the analysis conducted by PVsyst software, as observed in Figure 10, the daily solar energy reception potential in the horizontal position is approximately 5.4 kWh per square meter. By optimizing the tilt angles at 37 degrees, this potential reaches about 6.4 kWh per square meter; however, if the panels are placed in 2-meter rows due to space constraints, the reception potential will reach approximately 5.5 kWh per square meter. It is also worth noting that the simulation assumed no continuous shading from trees on the solar panels; if shading occurs, the system performance will be significantly lower than 5.5 kWh per square meter.

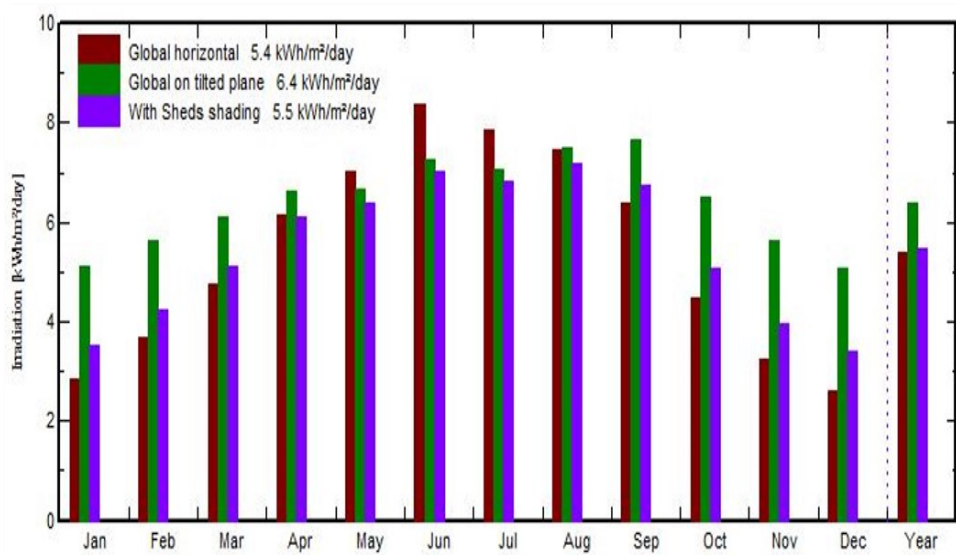


Figure 10. Solar energy yield in the tilted position with a 2-meter row spacing at a 37-degree angle

The annual solar energy potential of the considered system, as observed in Figure 11, is approximately 131,000 kWh. The highest solar energy potential occurs in June, and the lowest occurs in December and January. The reason for the better performance of solar modules in June (spring season) compared to the summer months is that solar modules experience a slight performance drop at excessively high temperatures.

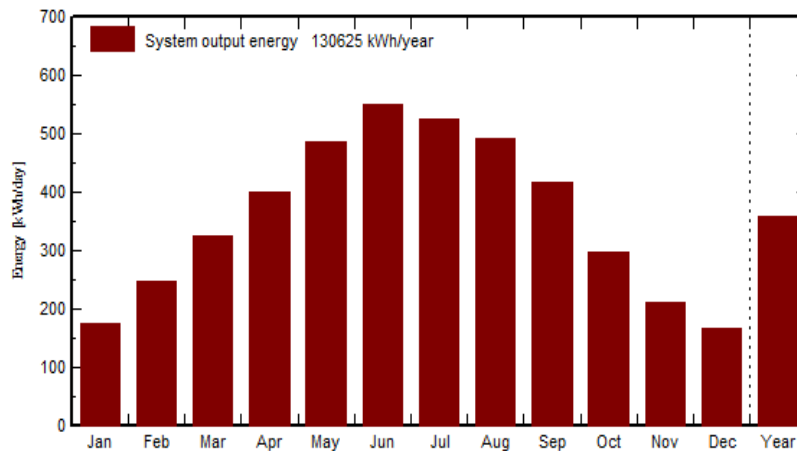


Figure 11. Annual solar energy potential of the system

The findings indicate the high efficiency of this technology. The optimal tilt angle of 37 degrees, resulting in 67% coverage of the canal surface, can generate approximately 131 MWh of electricity annually. Meanwhile, the shading effect is expected to reduce evaporation by up to 55%, equivalent to an annual water saving of 257.3 cubic meters. Economic analysis revealed that with an initial investment of 25 billion Rials, the combined annual benefits from electricity savings/revenue (2.34 billion Rials) and water savings (6.43 million Rials) result in a net annual profit of 2.346 billion Rials. This brings the payback period to 10.66 years. Assuming a standard useful life of 25 years for the system, the project will yield an average annual return on investment (ROI) of 9.4%.

This study demonstrates that covering canals with solar panels is a strategic, technical, and economic solution. This approach transforms water conveyance canals from passive infrastructure into multipurpose, dynamic assets, thereby contributing to water and energy security. This dual benefit reduces water losses and generates clean energy simultaneously, strengthening the vital Water-Energy Nexus. By providing a transparent economic model, this research equips water managers and policymakers with a powerful tool to make informed decisions regarding investments that enhance agricultural resilience to climate change in water-scarce regions. Furthermore, as a replicable model, this solution can serve as a foundation for macro-policies aimed at achieving Sustainable Development Goals (SDGs) related to water, energy, and the environment.

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