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Topic

Integrating Solar Photovoltaics to Decarbonize the Desalination industry in Algeria: A Case study of a Large-Scale Reverse Osmosis Plant in El Oued

On May 2025 in front of the jury committee:

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Abstract

Water scarcity is among the most pressing concerns for many parts of the globe, especially the arid and semi-arid areas like North Africa. Reverse Osmosis (RO) desalination units operated with fossil-based energy are predominantly used to secure clean water for these regions. Due to the rapid population growth—exceeding 44 million in Algeria as of 2024—this sector consumes substantial energy, with RO plants typically requiring 3 to 6 kWh per cubic meter of water. Consequently, the desalination sector contributes significantly to greenhouse gas emissions, estimated at over 1.5 million tons of CO_2 annually in Algeria alone.

Given Algeria's exceptional solar potential—averaging over 6.5 kWh/m²/day in the southern regions—the government has set ambitious goals to achieve 22 GW of renewable energy capacity by 2035. However, the intermittent nature of solar resources and high initial investment costs necessitate hybrid energy systems (HES), combining renewable sources with the national grid or energy storage solutions.

This thesis investigates the viability of integrating photovoltaic (PV) solar energy into the operation of large-scale desalination plants, focusing on a case study of a 30,000 m³/day RO unit in the Wilaya of El Oued. The research evaluates the techno-economic feasibility and environmental impacts of various scenarios with different PV penetration levels and electricity feed-in policies. Using HOMER Pro software, the study simulates optimal configurations for a grid-connected PV system, considering real energy consumption data and tariff structures.

Simulation results show that integrating PV can reduce grid electricity demand by over 50% and achieve a levelized cost of energy (LCOE) as low as 0.029 USD/kWh under projected 2030 costs. Moreover, annual CO_2 emissions could be reduced by more than 16,000 tons. These findings provide strong evidence for policymakers to support the deployment of solar energy as a means to decarbonize the water sector and enhance national energy-water security.

The findings of this thesis are significant and could help policy makers to make best decisions on the deployment of solar energy to decarbonise water sector in the country.

Key words: Water and energy security, desalination, solar energy, energy-climate-water nexus, techno-economic assessment, optimization.

الملخص:

ندرة المياه هي من بين أكثر القضايا إلحاحًا في العديد من مناطق العالم، خاصة المناطق الجافة وشبه الجافة مثل شمال إفريقيا. تُستخدم وحدات تحلية المياه بالتناضح العكسي (RO) التي تعمل بالطاقة الأحفورية بشكل رئيسي لتأمين المياه النظيفة لهذه المناطق. بسبب النمو السكاني السريع—الذي يتجاوز 44 مليون نسمة في الجزائر اعتبارًا من عام 2024—يستهلك هذا القطاع طاقة كبيرة، حيث تتطلب محطات التحلية بالتناضح العكسي عادةً من 3 إلى 6 كيلووات ساعة لكل متر مكعب من المياه. وبالتالي، يساهم قطاع التحلية بشكل كبير في انبعاثات غازات الدفيئة، حيث تقدر بأكثر من 1.5 مليون طن من ثاني أكسيد الكربون سنويًا في الجزائر وحدها.

نظرًا للإمكانات الشمسية الاستثنائية في الجزائر—بمتوسط يزيد عن 6.5 كيلووات ساعة/م²/يوم في المناطق الجنوبية—وضعت الحكومة أهدافًا طموحة لتحقيق قدرة 22 جيجاوات من الطاقة المتجددة بحلول عام 2035. ومع ذلك، فإن الطبيعة المتقطعة لموارد الطاقة الشمسية والتكاليف الاستثمارية العالية في البداية تستلزم أنظمة الطاقة الهجينة (HES)، التي تجمع بين المصادر المتجددة والشبكة الوطنية أو حلول تخزين الطاقة.

تبحث هذه الأطروحة في جدوى دمج الطاقة الشمسية الكهروضوئية (PV) في تشغيل محطات تحلية المياه الكبيرة، مع التركيز على دراسة حالة لوحدة RO بسعة 30,000 م³/اليوم في ولاية الوادي. تقيّم الدراسة الجدوى التقنية والاقتصادية والتأثيرات البيئية لمختلف السيناريوهات بمستويات مختلفة من اختراق الطاقة الشمسية الكهروضوئية وسياسات تغذية الكهرباء. باستخدام برنامج HOMER Pro، تحاكي الدراسة التكوينات المثلى لنظام الطاقة الشمسية المتصل بالشبكة، مع الأخذ في الاعتبار بيانات استهلاك الطاقة الحقيقية وهياكل التعريفات.

تُظهر نتائج المحاكاة أن دمج الطاقة الشمسية الكهروضوئية يمكن أن يقلل من طلب الكهرباء من الشبكة بأكثر من 50% ويحقق تكلفة موحدة للطاقة (LCOE) تصل إلى 0.029 دولار أمريكي/كيلوواط ساعة تحت التكاليف المتوقعة لعام 2030. علاوة على ذلك، يمكن تقليل انبعاثات ثاني أكسيد الكربون السنوية بأكثر من 16,000 طن. توفر هذه النتائج دليلاً قوياً لصانعي السياسات لدعم نشر الطاقة الشمسية كوسيلة لإزالة الكربون من قطاع المياه وتعزيز الأمن الوطني للطاقة والمياه.

الكلمات المفتاحية :الأمن المائي والطاقوي، تحلية المياه، الطاقة الشمسية، الترابط بين الطاقة والمناخ والمياه، التقييم التقني والاقتصادي، التحسين.

Dedicated to

MY PARENTS

MY FAMILY

MY COLLEGES

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Contents

Nomenclature

AC	Alternating current
AI	Artificial intelligent
BS	Battery storage
CO2	Carbon dioxide
COE	Cost of energy
CRF	Capital recovery factor
DC	Direct current
DG	Diesel generator
PV	Photovoltaics
RO	Revers Osmosis
HES	Hybrid energy system

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Introduction

General Context on Water Scarcity and Necessity of Desalination

Water scarcity represents a critical challenge in many parts of the world, particularly in arid and semi-arid regions such as North Africa. Algeria, the largest country in Africa, is situated in a Mediterranean climatic zone and is currently facing severe water stress in many regions. This situation is driven by a combination of factors including climate change, rapid population growth, urban expansion, and increased agricultural and industrial demands, all of which exacerbate pressure on the country's limited freshwater resources. As a result, Algeria must investigate long-term solutions to improve national water security and secure adequate supply for both residential and business sectors.

Given the scarcity of renewable freshwater sources and the predominance of arid conditions, Algeria has increasingly turned to non-conventional water resources. Ground water desalination has been used in the country for many years. However, seawater desalination last year emerged as a reliable and renewable solution, especially in coastal and water-stressed regions, where more than five desalination units have been installed and should be or will be start operation before the end of 2025. Both desalination systems contribute to reducing vulnerability to drought and supporting long-term socio-economic development.

Nonetheless, desalination facilities, like other systems, suffer several issues, including being very energy-intensive and having substantial environmental consequences emphasizing the need for more sustainable alternatives. The desalination industry is among the most energy-intensive sectors, with most facilities still relying on conventional fossil fuels for electricity generation. This dependence contributes to high carbon dioxide (CO_2) emissions, exacerbating global warming and environmental degradation. These energy and environmental concerns underscore the necessity of transitioning to cleaner and more sustainable energy sources for desalination processes.

One promising alternative is the use of solar photovoltaic (PV) technology, which offers a renewable, low-emission power source to energize desalination units. Algeria is endowed with some of the highest solar irradiance levels globally, especially in its southern desert regions [1], making solar energy a viable and attractive option for powering desalination plants.

PV systems convert solar radiation into electricity, enabling environmentally friendly operation of desalination facilities. Hence, integrating solar PV into desalination processes presents several advantages. Solar PV offers a renewable and clean energy that reduces greenhouse gas emissions and enhances energy security by decreasing reliance on volatile fossil fuels [2]. It virtually cost-free energy source once installed, leading to significant savings on electricity bills and reducing the financial burden on desalination plants. Although the upfront costs of installing solar panels and associated infrastructure may be high, the long-term benefits mostly outweigh the initial investment. These benefits collectively support Algeria’s goals of achieving sustainable water supply and reducing its carbon footprint.

Research Aim and Objectives

The aim of this study is to examine the viability of incorporating solar PV power into Algeria's desalination plants, case study of a large-scale RO desalination plant in the Wilaya of El Oued, southeast of Algeria. The main objective of this thesis is to study technoeconomic feasibility and environmental impacts of integrating solar PV with the electricity grid (grid-connected PV system) for decarbonisation of the selected desalination unit, considering different scenarios based on the rate of renewable energy contribution, selling electricity to the grid and the variation in PV costs. The proposed system is supposed to minimize energy consumption from fossil fuels, reduce energy costs (bills), mitigate GHG emissions and minimize peak loads in summer periods at the study location. HOMER pro software was used to achieve the goals of this thesis, which is commonly used for analysing hybrid energy systems (HES), for both grid-connected and off-grid applications [3].

This remaining part of this thesis is structured as follows. Chapter 1 provides the literature review on the relevant studies and explaining key concepts on water desalination and PV systems. The detailed description of used materials and methods are presented in chapter 2. Finally, the obtained results are presented and discussed in chapter 3. Thus, the key conclusions, study limitations and future work are outlined in the thesis conclusion.

Chapter 1: Literature Review

Chapter 1. Literature Review

1. Introduction

Growing scholarly interest in the nexus between renewable energy and desalination technology has been spurred by the shift towards sustainable water production in arid and semi-arid locations. The present level of knowledge on RO desalination, issues with energy consumption, and the possibility of using photovoltaic (PV) systems to decarbonize the process are all examined in this review of the literature. This section offers a thorough summary of the scientific and technological foundation supporting the integration of PV systems with RO desalination, drawing on international case studies, technical analyses, and regional evaluations, particularly within the Algerian setting. The special potential brought about by El Oued Province's distinct solar and hydrological circumstances are also highlighted, along with important developments and challenges.

2. Desalination and Energy Consumption

Desalination is now a crucial aspect of national water policies due to growing worries about water scarcity, especially in arid and semi-arid countries like the Middle East and North Africa. Because of its scalability and very low heat requirements, reverse osmosis (RO) has become the most energy-efficient membrane-based desalination technology. RO systems produce drinkable water by removing salts and contaminants from saline water using high-pressure pumps and semi-permeable membranes [4].

Desalination has been an integral component of Algeria's water policy, and the country has heavily invested in desalination plants as a way of guaranteeing a constant water supply [5]. The widespread application of desalination technologies has allowed Algeria to reduce its dependence on conventional sources of freshwater and defy the effects of droughts and unpredictable rainfalls. Algeria currently has one of the largest desalination capacities in Africa, with a few plants located along the Mediterranean coast and in desert regions. Among the different technologies for desalination, reverse osmosis (RO) is the most prevalent and successful technology employed. RO technology is favoured due to its economic feasibility, relatively high recovery rate, and ability to produce high-quality drinking water. Despite these advantages, desalination is an energy-intensive process and requires huge amounts of electricity to power high-pressure pumps to force seawater through membranes to remove salt and impurities. Such heavy utilization of energy increases not just operational costs but also worsens environmental decline, particularly if fossil fuels are the primary source of power.

But even with its effectiveness, energy use is still a major limitation. According to Ghaffour et al. [6], RO plants usually use 3–6 kWh/m³ of treated water, depending on the energy recovery device efficiency, membrane configuration, system recovery rate, and feed water salinity. In addition to raising operating expenses, this consumption—especially when fossil fuels are used—also raises indirect carbon emissions. As a result, lowering energy consumption or replacing it with renewable energy sources has become essential to the sustainability of desalination [7]. Additionally, 30 to 50 percent of a desalination plant's overall operating costs are tied to electricity [8], which makes the switch to renewable energy not only environmentally required but also long-term financially appealing.

3. Photovoltaic Solar Energy in Algeria: Potentials and Opportunities.

Algeria has one of the world's largest solar potentials. The country's average global horizontal irradiance (GHI) is above 5.5 kWh/m²/day, with southern regions like El Oued, Ouargla, and Adrar receiving over 6.5 kWh/m²/day and more than 3,500 hours of sunshine each year, according to the International Renewable Energy Agency [9]. These circumstances foster an atmosphere that is conducive to the widespread use of photovoltaic (PV) technologies.

At the same time, the price of solar PV modules has significantly decreased worldwide. According to IRENA [9], between 2010 and 2020, the levelized cost of energy (LCOE) from solar PV decreased by 80%, mostly due to enhanced production, economies of scale, and technological innovation. For industries with significant energy demands, like desalination, this decrease makes solar photovoltaics a feasible substitute, especially in isolated or off-grid areas.

In line with Algeria's national strategy to encourage the integration of renewable energy, the installation of decentralized PV systems offers a dependable way to power distant desalination plants without depending on erratic grid connections or expensive diesel generators [10].

4. Integration of PV Systems with RO: Global Experiments and Studies

4.1. RE supply option hierarchy in ZEB

Reverse osmosis unit (PV-RO) integration with solar systems is becoming more widely acknowledged as a viable way to reduce carbon emissions and energy expenses. The viability, scalability, and operational difficulties of this integration have been evaluated through a number of international case studies and research initiatives.

In their thorough analysis of PV-powered water pumping and desalination systems, Chandel et al. [11] came to the conclusion that direct PV-to-RO coupling works well for small- and mediumsized applications, particularly in dry or rural areas. To combat solar intermittency, they underlined the need for hybrid solutions (PV + grid or PV + battery) for high-capacity operations.

Al-Karaghouli and Kazmerski [12] conducted a techno-economic evaluation of small-scale PV-RO systems in desert conditions and discovered that, in comparison to traditional diesel-powered desalination, carbon emissions might be decreased by over 60%. They also reported

considerable fuel and maintenance cost reductions.
Gude [7] investigated a solar-powered RO system in India and showed that the costs of producing water might be reduced by 20–30%. They attributed these savings to the removal of fuel costs and the optimization of operations through intelligent control systems.
Similar initiatives in the UAE (such as Masdar's solar desalination program), Saudi Arabia (such as the King Abdulaziz City for Science and Technology's PV-RO pilot), and Tunisia have demonstrated that PV-RO systems can achieve operational stability and sustainability when combined with energy storage technologies.

5. Technical and Economic Challenges of PV-RO Integration

Despite the growing interest and potential of PV-RO systems, several technical and economic barriers continue to hinder their widespread deployment:

5.1. Energy Intermittency

Because of variations in sun irradiation, PV output is intrinsically variable. The continuous operation of RO pumps, which need steady pressure and flow, may be impacted by this. Reliability is frequently ensured by solutions like hybrid systems (PV-grid) or battery storage (e.g., lithium-ion, flow batteries) (Chandel et al., 2015) [11].

5.2. High Capital Costs

The initial investment needed to establish a full-scale PV-RO system, particularly with storage and control systems, is still substantial even though the cost of PV modules has decreased. For big desalination facilities aiming for an output of more than 1,000 m³ per day, this could be a significant challenge [12].

5.2.1. Maintenance and Monitoring

Dust collection (soiling) is a problem for PV systems in arid locations, which drastically lowers system efficiency. To guarantee long-term performance, this calls for routine cleaning, observation, and perhaps automated self-cleaning systems.

6. The Algerian Context: Challenges and Opportunities in El Oued Province

Most desalination plants in Algeria are either diesel generator-powered or connected to the national grid, indicating the country's continued heavy reliance on conventional energy. High energy use and considerable greenhouse gas emissions are the results of this. Targeting important industries including water, agriculture, and distant electrification, the government's National Renewable Energy and Energy Efficiency Program (2020–2035) intends to diversify the energy mix by adding up to 22,000 MW of renewable energy (Ministère de la Transition Énergétique, 2020).

The southeast Algerian province of El Oued offers a perfect setting for testing extensive PV-RO systems. The region's high sun irradiation, low cloud cover, and abundance of saline groundwater are all advantageous for the deployment of solar PV-powered decentralized desalination, according to Aguersif et al. (2020).

Furthermore, the construction of massive PV arrays with little shade or space restrictions is made easier by the availability of wide-open ground. By putting such systems in place, water production's energy footprint may be significantly decreased, regional water security could be enhanced, and sustainable rural development could be supported.

7. Conclusion

A clear path toward more environmentally friendly and energy-efficient water treatment systems is revealed by the combination of scholarly and technical material on reverse osmosis (RO) desalination with photovoltaic (PV) energy integration. Because it requires less energy and is easier to use than conventional thermal processes, reverse osmosis has become the desalination technology of choice. Energy usage, which ranges from 3 to 6 kWh per cubic meter, is still a major problem for the environment and economy, especially in large-scale installations where carbon footprints and electricity costs are high.

The architecture of desalination systems has changed as a result of solar photovoltaic technology's rise as an affordable and scalable energy source. Significant advancements in efficiency and control technology, along with sharp drops in PV costs over the last ten years, have created new opportunities for the direct integration of renewable energy into water infrastructure. The potential for PV-RO integration is especially intriguing in sun-rich nations like Algeria, where average solar irradiation exceeds 5.5 kWh/m²/day and reaches over 6.5 kWh/m²/day in the southern regions.

Experiences from throughout the world, such as fruitful pilot programs in North Africa, the Gulf states, and India, offer important insights into the operational factors and technical setups of PV-RO systems. Research highlights the significance of energy storage options, sophisticated control systems (MPPT, VFD), and adaptive design strategies that take into account solar energy's sporadic nature. Additionally, there is evidence that incorporating PV into desalination can result in up to 60% lower carbon emissions and 20–30% lower long-term operating costs, which makes it a desirable route for decarbonizing the water industry.

The literature highlights both potential and challenges in the Algerian environment. There is a rising national movement to switch to renewable energy, even though the majority of desalination facilities now in operation rely on diesel generators or grid electricity, which results in significant emissions and a reliance on fossil fuels. Water is one of the critical sectors where the National Renewable Energy Strategy (2020–2035) emphasizes the need of implementing clean energy. El Oued Province is ideally suited for the large-scale deployment of PV-powered RO systems due to its arid climate, high groundwater salinity, and remarkable solar potential.

In addition to confirming that PV-RO integration is feasible, this body of literature emphasizes the necessity of context-specific design, strong regulatory backing, and continuous innovation. The case study in this thesis, which aims to evaluate the technical and financial viability of installing a large-scale PV-RO system in El Oued, is critically based on the findings. The study intends to significantly aid Algeria's transition to sustainable water and energy systems by firmly establishing the analysis in both local environmental conditions and international best practices.

Chapter 2: Methodology

Chapter 2. Methodology

1. Introduction

This chapter outlines the methodological framework adopted to assess the technical, economic, and environmental feasibility of integrating photovoltaic (PV) solar energy into the operation of a large-scale reverse osmosis (RO) desalination plant in El Oued, Algeria. The methodology was designed to ensure a comprehensive evaluation of the hybrid energy system (HES) configuration, including solar resource availability, energy demand estimation, system sizing, and performance simulation under various operational scenarios.

To achieve this, a combination of real operational data, mathematical modeling, and simulation using the HOMER Pro software was employed. The approach integrates both quantitative and qualitative assessments, enabling a robust analysis of cost structures, energy performance indicators, and environmental impacts, such as carbon dioxide (CO_2) emission reductions.

This chapter is structured as follows: Section 2 describes the modeling of the grid-connected PV system and its components (PV modules, converter, grid interface). Section 3 details the solar resource analysis and system design criteria. Section 4 presents the techno-economic assessment methodology using HOMER Pro. Section 5 addresses the environmental evaluation, particularly CO_2 emissions mitigation. Section 6 explains the operational scenarios and grid tariff implications. Finally, Section 7 summarizes the key steps of the adopted methodology.

2. Overview of the Methodological Framework

To assess the viability of incorporating photovoltaic (PV) solar systems into the functioning of a large-scale reverse osmosis (RO) desalination plant in El Oued, Algeria, this study used a thorough methodology. The method is set up to address environmental sustainability, system design and optimization, solar resource analysis, energy demand assessment, and economic viability. A hybrid configuration—solar PV and grid power is analysed using real data (utility tariff data, energy use) and practical operating assumptions using the simulation tool (HOMER Pro). The detailed description of the materials used (including data sources, location characteristics, …etc.) and the employed methods (including mathematical modelling, simulation tools, …etc.) are presented in the following sections.

3. Modelling of the grid-connected PV system

As described above, HES includes different components. The main energy sources, energy storage, and electronic devices that are used in this work are described and modelled as follows.

3.1. Solar PV

Solar PV panel is a device that converts solar energy into electrical energy. The power supplied by the PV can be calculated by a function of the solar radiation and ambient temperature using Eq. 1 [13]:

$$P_{pv} = P_{Npv} \times \frac{G}{G_{ref}} \times \left[1 + K_t \times \left(\left[T_{amb} + \frac{NOCT - 20}{800}\right] \times G - T_{ref}\right)\right] \quad (1)$$

Where Ppv and PNpv are the output power and rated power of PV module respectively. G and Tamb are the solar radiation and ambient temperature at time step simulation. However, Gref (1 kW/m²) and Tref (25°C) are solar radiation and ambient temperature at standard conditions. Kt is the temperature coefficient of power depends on PV's panel technology. NOCT (nominal operation cell temperature).

Solar PV panel is a device that converts solar energy into electrical energy. Solar energy is the abundant renewable source in Algeria. Photovoltaic panels are used to convert this energy into electricity. Energy output of the PV panel has simulated using the one-diode model [14]. The I-V curve can be expressed by Eq. 2-4 as follows:

$$I(V) = I_{ph} - I_o[e^{\left(q\frac{V+IR_S}{nkTN_{cs}}\right)} - 1] - \frac{V+IR_S}{R_{sh}}. \quad (2)$$

$$I_{ph} = \frac{G}{G_O}[I_{ph,STC} + \gamma(T - 298)]. \quad (3)$$

$$I_O = I_{O,STC}\left(\frac{T}{298}\right)^3 e^{\left[\left(\frac{qE_g}{nk}\right)\left(\frac{1}{298} - \frac{1}{T}\right)\right]}. \quad (4)$$

Where I and V are respectively current and voltage of the PV module their values are varied according to available solar irradiation and ambient temperature. Hence, the output power of the PV module is evaluated. I_{ph} is the photocurrent, I_o is the diode reverse saturation current.

Where G is the available irradiance, G_O reference irradiance (1000 W/m²) and T is the ambient temperature. γ is the temperature coefficient of short-circuit current.

3.2. Grid

Grid. When the PV system and storage devices are not sufficient to supply the load, the grid is used to supply the deficit power. In Algeria, the purchase price of electricity (EPR) without subsidies is 0.1 $/kWh [14] and 0.05 $/kWh with state subsidies.

3.3. Converter

Converter is the device that converts the electrical energy from AC into DC or vice versa. The rated power of the convertor depends on the peak load. The efficiency of the converter ($\boldsymbol{\eta}$Cnv) can be approximated by Eq. 5 [13].

$$\eta_{Cnv} = \frac{P_{output}}{P_{input}} \tag{5}$$

Generally, the converter's efficiency is assumed 95 % with lifetime of 15 years.

3.4. Energy Demand Assessment of the RO desalination Plant

The study's chosen a RO desalination facility located in El Oued, which produces 30,000 cubic meters of water per day. According to regional case studies and estimations from the literature, RO systems usually use 3–5 kWh/m^3 of desalinated water [15]. With an average load of 3.75 to 6.25 MW, the plant's daily energy consumption is estimated to be between 90,000 and 150,000 kWh/day.

In our study, the energy demand for the year 2024 (12 moths, specifying the energy use in daytime and night periods) for the selected RO desalination unit is collected from the national electricity distribution company SONELGAS, directional division of El Oued. This demand is then used to estimate the hourly energy consumption for the unit and then defined in HOMER Pro, under the load demand component. The ability to enter hourly demand data into HOMER Pro makes it possible to accurately depict how the system would behave in actual operating circumstances. In addition, HOMER pro, provides the hourly, daily, monthly load profile with the model outputs.

4. Solar Resource Analysis and PV System Design

The southern Algerian province of El Oued is known for its great potential for solar irradiation, with an average global horizontal irradiance (GHI) of 6.5 kWh/m²/day. The NASA Surface Meteorology and Solar Energy Database or other high-resolution sources, such PVGIS, have been used to gather data on solar radiation through an import tool available in HOMER pro [16] [17]. Therefore, the design of PV system can be performed. However other data also are needed, including:

- Selection of PV panel type and manufacturing company (polycrystalline or monocrystalline for higher efficiency, and local or foreign company according to availability and market costs)
- Panel orientation and tilt angle selection (simply optimized based on latitude (~33.4° N))
- Sizing of inverters, combiners, and wiring infrastructure and other electronic devices
- Consideration of performance ratio losses such as temperature derating, soiling (common in desert regions), and inverter losses (a derating factor of 80% is commonly defined).

Land use requirements are also calculated, estimating approximately 8,000 m^2 per MW installed, depending on panel efficiency and spacing. The layout must consider available land, shading, and ease of maintenance [18]. However, due to time constraints, this type of spatial analysis will be investigated in future thesis separately. Hence, in this study, we have considered that the required land for installing PV system is available as the unit has large free space not exploited.

5. Techno-economic assessment of the grid-connected PV system with HOMER Pro

HOMER pro software is a powerful tool for designing of HES to determine optimal size of its components through carrying out the techno-economic analysis. It performs three main analytical stages: simulation, optimization, and sensitivity analysis. HOMER includes a comprehensive component library encompassing conventional and renewable power sources (such as Wind turbines, PV panels, fuel cells, small hydropower, biomass, and conventional generators), energy storage technologies (batteries and hydrogen), electronic devices (converter), and control systems. Its core input parameters include site-specific climate data, system component costs, and electrical load profiles [19]. The software evaluates various system configurations and ranks them based on the net present cost (and evaluates the levelized cost of energy (COE) as the main output), aiding in the selection of the most economically viable solution. In hybrid energy systems (HES), HOMER also supports various dispatch strategies such as Load Following (LF) and Cycle Charging (CC), and users can select one or more controllers and let the software optimize.

HOMER pro can solve the optimization problem of HES in grid- connected and off-grid modes. HOMER pro design hybrid systems based on the model inputs, including the detail of cost parameters used in the system (namely investment cost, replacement cost, and operation & maintenance (O&M) cost), tariffs of grid purchase and sellback, and other techno-economic constraints [18]. The model input and output variables that mostly located in any HOMER pro model are:

1. **The model inputs:**

- Capital cost of PV ($700-$1,200/kW depending on market conditions)
- Operation and maintenance costs ($10-$20/kW/year)
- Grid electricity tariff (from user-provided data)
- Project lifetime (20-25 years)
- Discount rate (6-10%)

2. **The model outputs:**

- Net Present Cost (NPC) in USD
- Levelized Cost of Energy (LCOE) in USD/kWh
- Payback period (years)
- Annual energy savings (kWh)
- Emissions (kg Co_2/year)

It is also important to perform a sensitivity analysis on the studied system to test how changes in some variables (like PV costs, grid costs, and minimum renewable fraction) can affect system viability and sustainability. Thus, A sensitivity analysis is performed in this work based on changing the values of minimum renewable fraction.

6. Environmental Impact Assessment

By using solar photovoltaics instead of fossil fuel-based electricity, the reduction in carbon footprint can be evaluated to assess the environmental sustainability of the proposed system. In our study, the annual CO_2 savings are calculated using the average grid emission factor (0.88 kg CO_2/kWh). For example, if PV supplies 60% of the 120,000 kWh/day average demand:

- Annual PV energy: 26,280,000 kWh
- CO_2 reduction: 16,556 tons/year

Life Cycle Assessment (LCA) may also be considered for detail environmental sustainability assessment which enable incorporating embedded emissions in PV system manufacturing [20], however this type of analysis is not considered in this thesis but will be included in future work.

7. Operational Scenarios, Grid tariffs and Impacts

It is believed that the desalination plant's current energy source is entirely reliant on the national grid, and modelling is done using actual electricity bills. As the proposed PV system is discussed in the grid connected application, several configurations are considered to compare the suggested hybrid system within the baseline scenario (where the unit is only operated with the grid).

- **Scenario A:** Grid only
- **Scenario B:** PV + Grid (Hybrid energy system)

In addition, the system performance is also evaluated in terms of:

- Grid dependency
- System reliability (unmet load percentage)
- PV penetration ratio (renewable fraction)
- Excess electricity production (potential for feed-in if policies allow and technically viable solution)

These operational scenarios enable comparison between system reliability, operational costs, and fuel/emissions reductions and assess how resilient the proposed hybrid system is across daily and seasonal variations.

8. Conclution

This chapter described in detail the used materials and employed methods for achieving the objectives of this thesis. Here, assessing the potential of grid connected PV system to decarbonise the selected desalination unit is performed by utilizing real data, and strong techno-economic reasoning.

Based on these collected real data, and stated assumptions, the proposed system is simulated in HOMER pro software using several scenarios. However, the obtained results are presented and discussed in the following last chapter: results and discussion.

Chapter 3: Case study simulation, results and discussions

1. Introduction

This chapter presents the simulation results and discusses the technical, economic, and environmental performance of the proposed grid-connected photovoltaic (PV) system for a large-scale reverse osmosis (RO) desalination plant located in El Oued, Algeria. Building upon the methodological framework outlined in Chapter 2, this section applies real-world energy consumption data and high-resolution solar resource information to evaluate the performance of various hybrid energy system (HES) configurations under different scenarios.

The simulation was conducted using HOMER Pro software, which optimizes the system components based on cost, reliability, and environmental criteria. Four operational scenarios were analyzed, covering combinations of current and projected PV costs, with and without the option of selling excess electricity back to the grid. Key performance metrics such as net present cost (NPC), levelized cost of energy (LCOE), renewable fraction, and CO_2 emission reductions were computed and compared across scenarios.

This chapter is organized as follows: Section 2 describes the case study location and local solar and climate conditions. Section 3 details the modeled energy system in HOMER Pro and the technical specifications of the plant. Section 4 presents the simulation results for each scenario, followed by a comprehensive discussion in Section 5. Section 6 addresses the system's challenges and limitations, while Section 7 provides a comparative analysis with previous studies and formulates policy and technical recommendations.

2. Case study location and resources

The proposed grid-connected PV system has been optimized to electrify a selected desalination unit located in El Oued as shown in Fig.1.

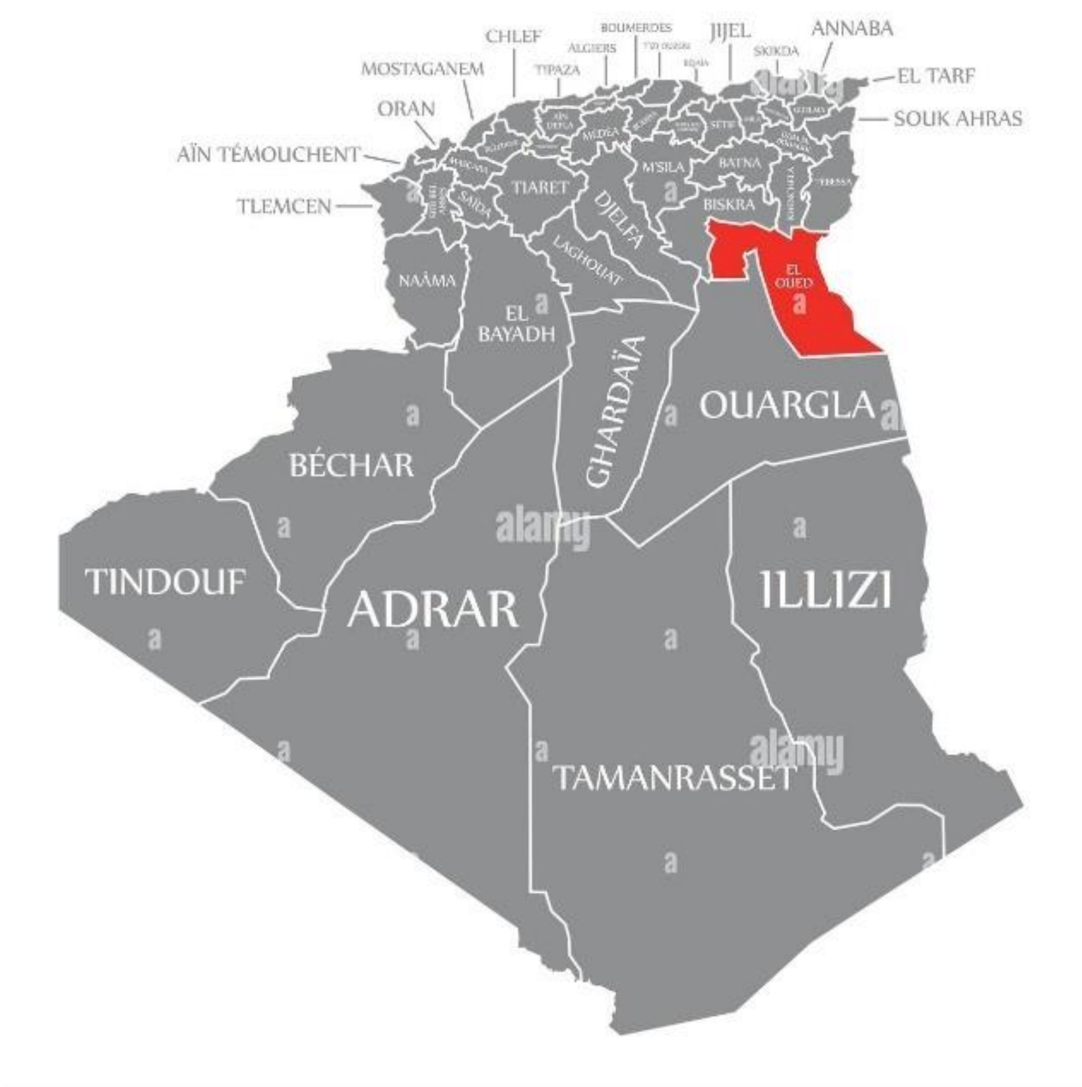


Figure 1. The geographic location of El oued.

However, the climatic data for El Oued, including ambient temperature and solar irradiation and clearness index are given in Fig.2 and Fig.3 respectively.

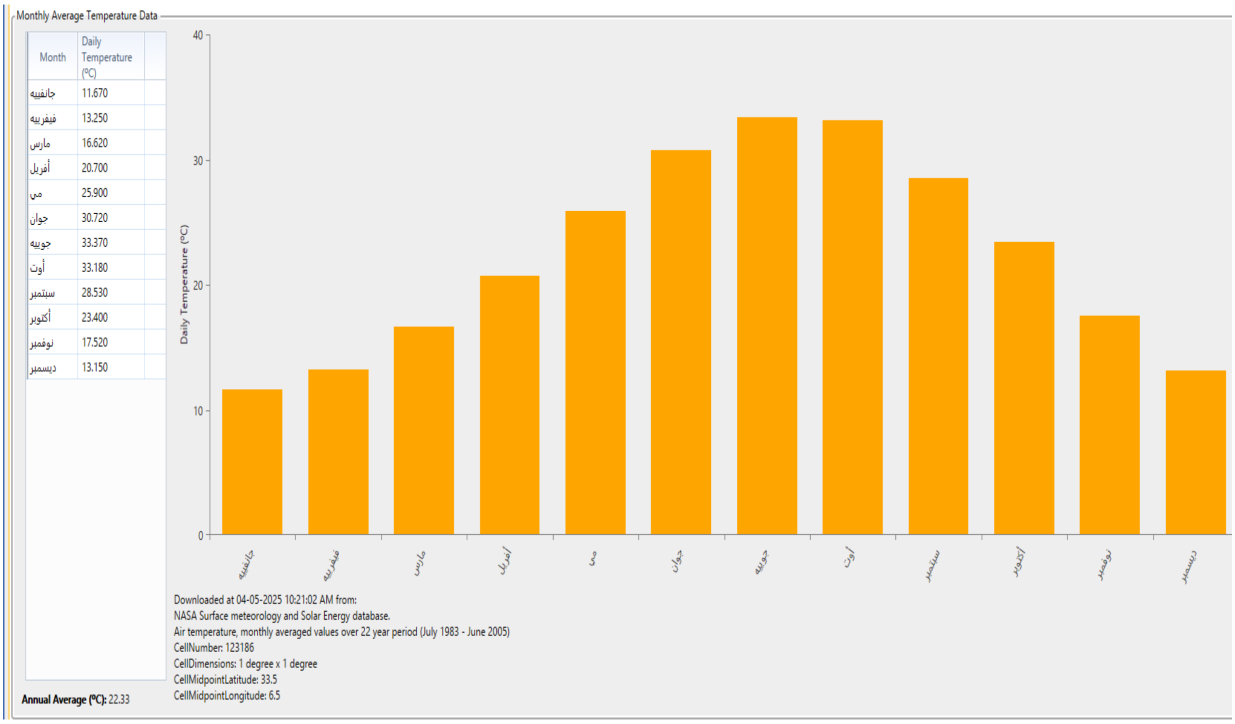


Figure 2. Hourly ambient temperature at El Oued

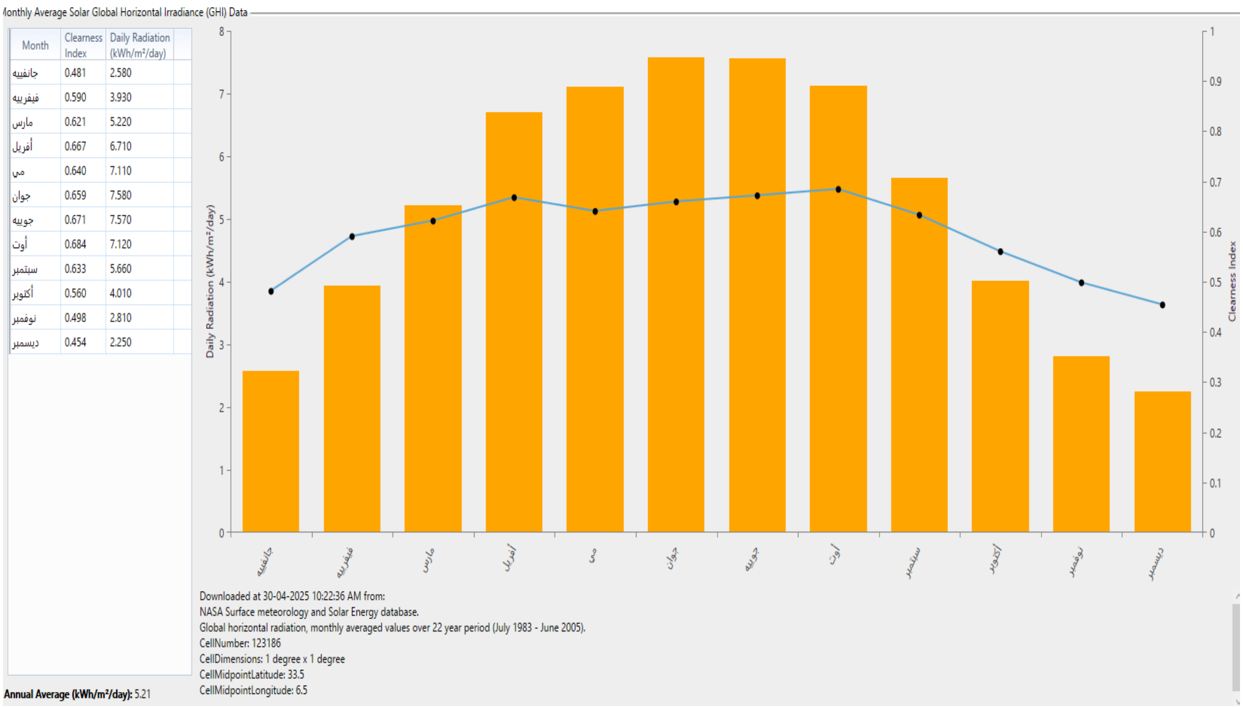


Figure 3. Solar radiation and Clearness Index at El Oued.

3. Model of the grid connected PV system in HOMER pro

The proposed grid-connected PV system that includes PV, utility grid, convertor, and load demand as presented in Fig.4, is modelled and simulated to find the optimal configuration for the electrification of the selected desalination unit. The peak load is found 743.47 kW, with an average daily consumption of 8486 kWh/day.

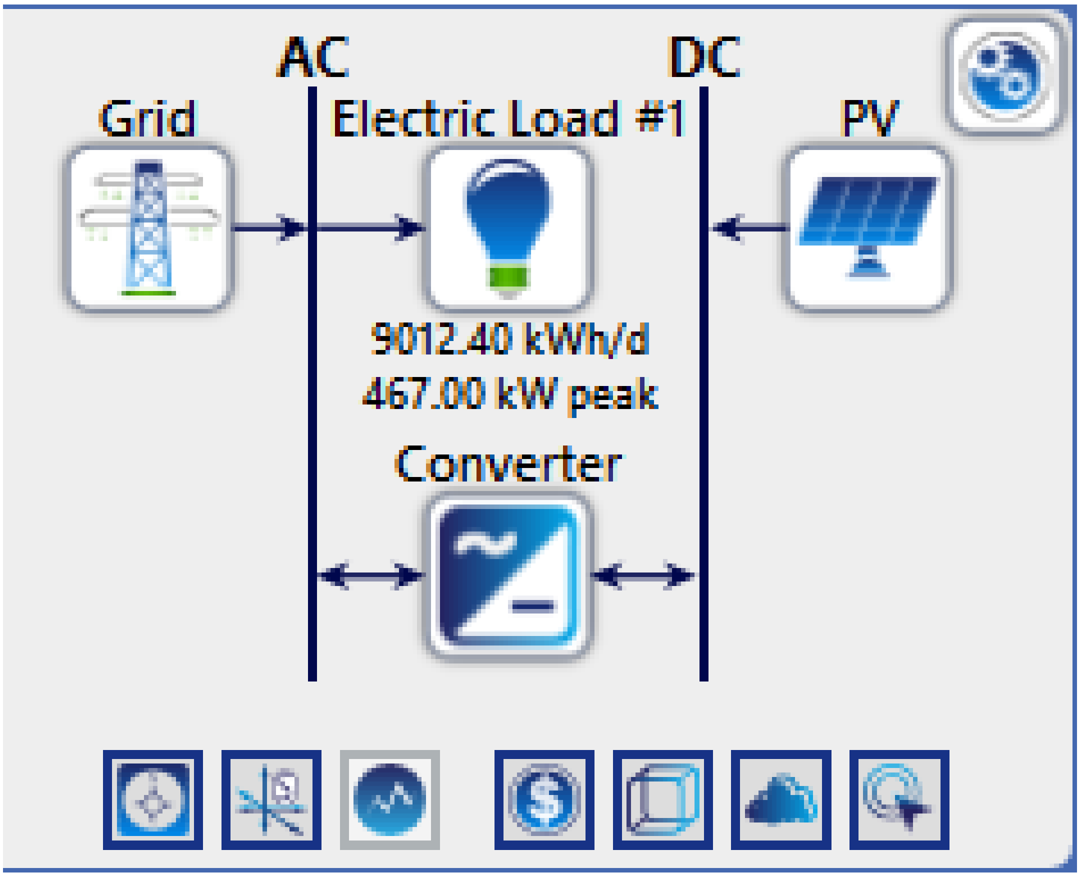


Figure 4. Schematic of the grid connected PV hybrid system.

3.1.1. Case study description and load estimation

In this study, a large-scale reverse osmosis (RO) desalination plant located in El Oued Province is selected as the case study. The plant is representative of typical water treatment infrastructure in arid Algerian regions, where high solar potential can be strategically utilized to reduce grid dependency and lower CO_2 emissions.

The roof area and available land surrounding the desalination facility have been evaluated for solar PV system installation, with a total usable roof surface of approximately 1446 m², which will be dedicated to photovoltaic panel deployment.

The energy demand of the plant is estimated based on typical energy consumption data for large-scale RO units, literature benchmarks, and operational parameters from similar desalination facilities. For a treatment capacity of 30,000 m³/day, and an average energy intensity of 3–5 kWh/m³, the plant's daily energy demand is calculated to be approximately 90,000 to 150,000 kWh/day, with peak electrical loads reaching up to 5 MW, depending on system configuration, pumping stages, and operating pressure.

The seasonal load profile of the plant reflects variations in water demand and operational performance, which are influenced by ambient temperature, groundwater salinity, and regional water supply needs. These factors were integrated into the HOMER Pro model to develop an accurate representation of load variability and inform the PV system design and hybrid grid integration.

Fig.5, Fig.6, and Fig.7 shows respectively, the daily, seasonal and yearly load profile of the RO desalination unit.

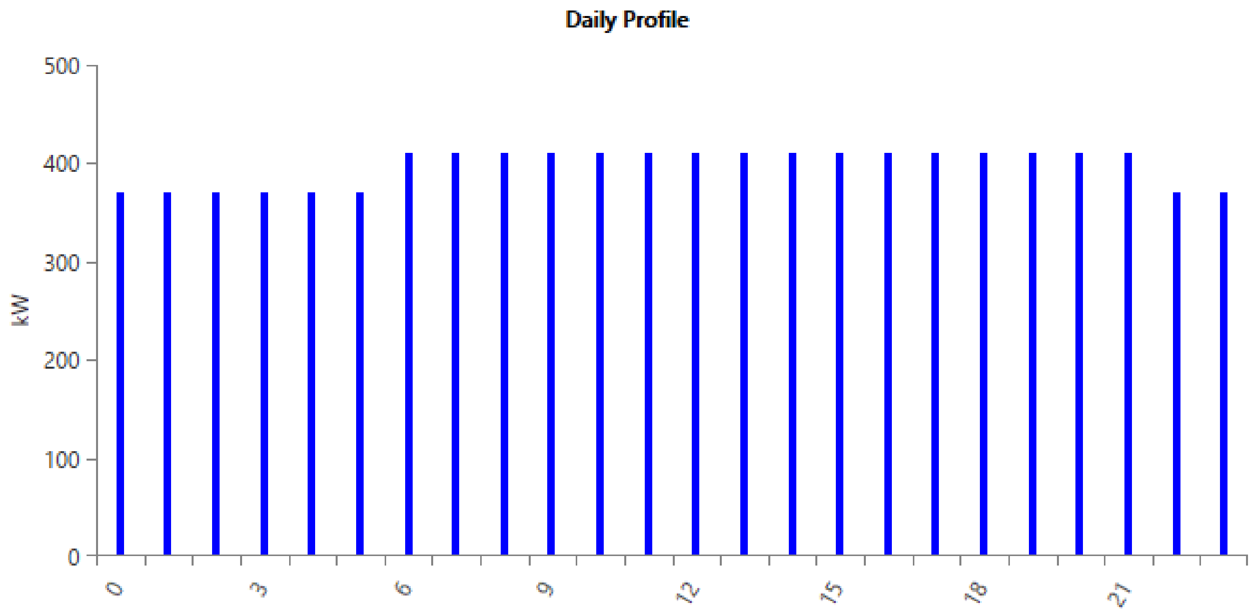


Figure 4. The daily load profile of the RO desalination unit.

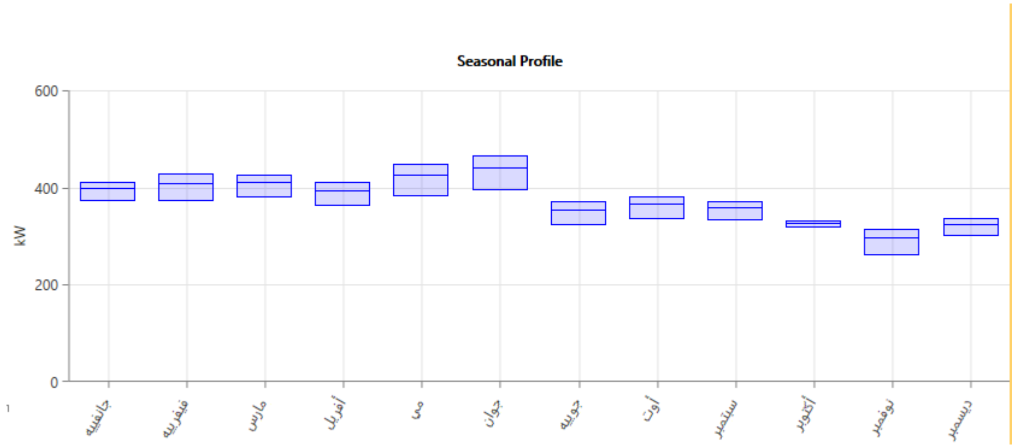
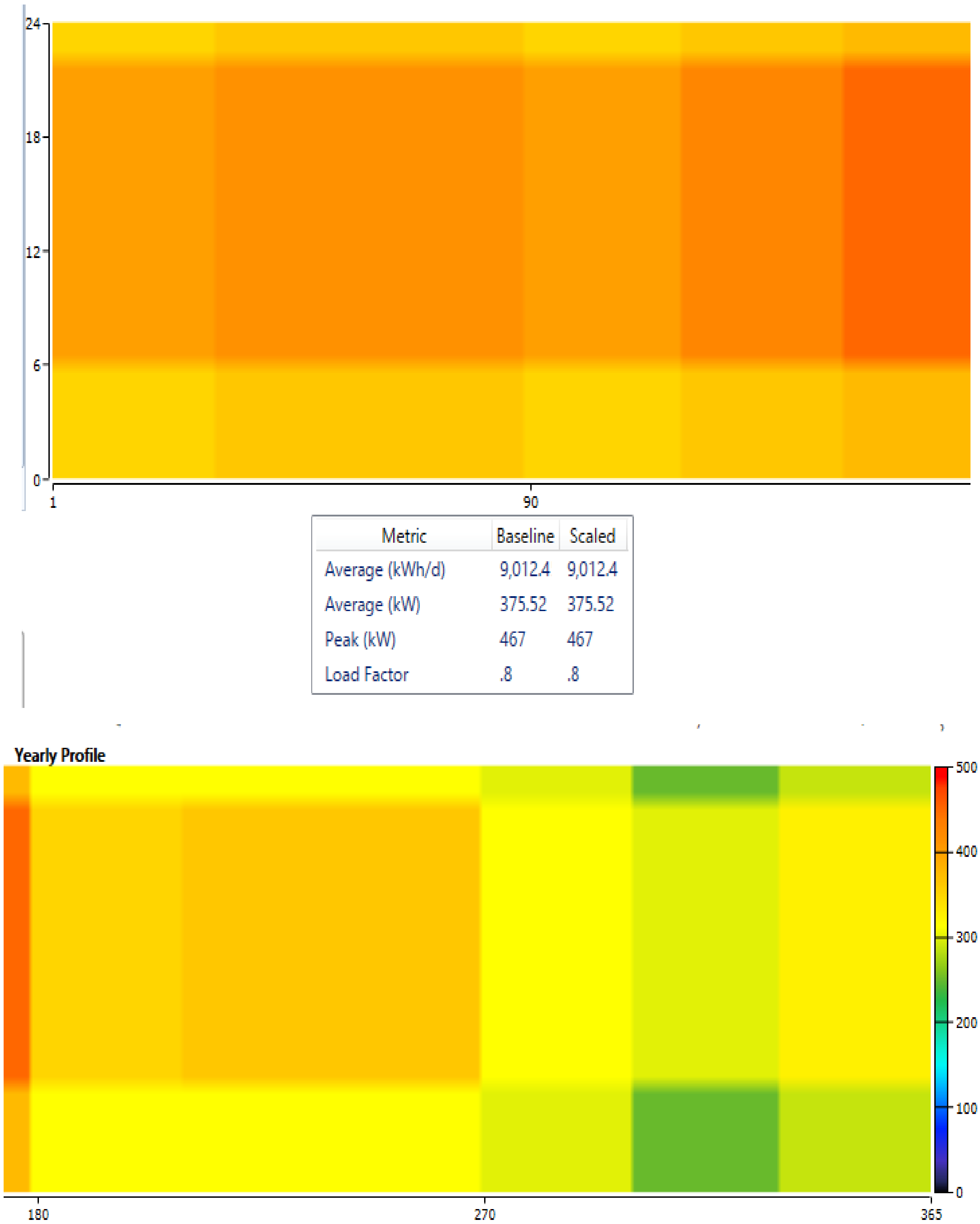


Figure 5. The seasonal load profile of the RO desalination unit.



Metric	Baseline	Scaled
Average (kWh/d)	9,012.4	9,012.4
Average (kW)	375.52	375.52
Peak (kW)	467	467
Load Factor	.8	.8

Figure 6. The yearly load profile of the RO desalination unit.

3.1.2. Techno-economic data for the model input

The solar PV panel used in this work has the following characteristics. The cost of capital and replacement, operation and maintenance (O&M) for both PV panels is $1000/kW and $10/KW respectively [21]. Tab.1 shows the characteristics of the selected PV panel model. Solar panels are installed with an optimum inclination angle (equal to the latitude of El Oued that is 33.35 °) and oriented to the south.

Table 1. Technical economic data of PV panels.

Component	Generic PV-300Wc
Model	Monocrystalline-crystalline
Capital cost($/KW)	10000
Capital cost at 2030 ($/KW)	500
O&M Cost ($/KW/year)	10
Lifetime (year)	25
Efficiency (%)	18
Derating factor (%)	88
Maximum Capacity (KW)	NA

The converter's rated power is optimised by HOMER pro and depends on the peak load. The Converter's efficiency is set at 95 % and its lifetime is set 15 years. The converter's capital cost and replacement cost are the same and are taken at $300/kW. The project lifetime is set to be 25 years, and the real discount rate is defined 6 %.

The targeting minimum renewable energy fraction (contribution) of 10 % to the total energy mix is defined for all scenarios. Given the nature of the hybrid system, carbon dioxide (CO_2) emissions are primarily associated with grid electricity consumption, which represents the dominant source of lifecycle emissions—estimated at 0.88 kg CO_2-equivalent per kWh, based on national grid characteristics.

3.1.3. Simulation of the proposed energy system

After gathering all the necessary data for doing the techno-economic assessment, all the inputs are defined in HOMER pro and starting the simulation with an hourly time step for the overall year (8760 hours). In this study both Load Following and Cycle Charging control strategies are selected and let HOMER pro optimize the system. Even though the Load Following strategy is more suitable for variable renewable energy integration. The software evaluates various system configurations and ranks them based on the lowest net present cost (NPC). However, the Levelized Cost of Energy (LCOE) is the critical metric for comparing the economic performance of various energy generation systems, especially when evaluating renewable integration into energy-intensive applications such as seawater desalination.

In addition to LCOE, other parameters are evaluated, namely CO_2 emissions, renewable energy fraction, overall system cost, among others. These outputs are essential for evaluating the technical, economic and environmental sustainability needed for assessing the overall sustainability of energy systems. The results obtained are presented below according to the two scenarios investigated.

4. Results and discussion

After determining the components of the Hybrid Energy System (HES), the simulation was conducted using the HOMER Pro software. This part of the study aims to analyze the technical, economic, and environmental feasibility of integrating the photovoltaic (PV) system with the electrical grid to meet the needs of the desalination plant in Al-Wadi Governorate. Two different scenarios were analyzed, by performing a sensitivity analysis based on current and projected PV costs to evaluate the performance of the hybrid systems. For each scenario, two varying operating conditions are discussed, selling back the excess electricity from PV to the grid and without selling back to the grid. As a result, four scenarios are simulated, presented and discussed as follows.

4.1. The First scenario (current costs without selling back to grid)

This scenario represents current PV costs without selling back the excess from PV to the grid. The results of the HES configuration and the techno-economic and environment variables related to it are given in Tab.2.

Table 2. The result of HES (for the first scenario without sellback to the grid).

Architecture/PV (kW)	Architecture/Grid (kW)	Architecture/Converter (kW)	Architecture/Dispatch
6702.620332	999999	447.9619422	CC
Cost/COE ($/kWh)	Cost/NPC ($)	Cost/Operating cost ($)	Cost/Initial capital ($)
0.03009748	1360226	89639.13	201414.8
System/Ren Frac (%)	System/Elec Prod (kWh/yr)	System/Elec Cons (kWh/yr)	System/CO2 emissions (kg/yr)
51.15017	1.389632E+07	3495956	948845.9
PV/Capital Cost ($)	PV/Production (kWh)	Grid/Energy Purchased (kWh)	Grid/Energy Sold (kWh)
67026.2	1.218855E+07	1707769	206430

Fig.8 shows the electricl energy flows within the designed HES for the first scenario, including electricity generated by PV, excess electricty, the contribution of the grid as well as the PV among others.

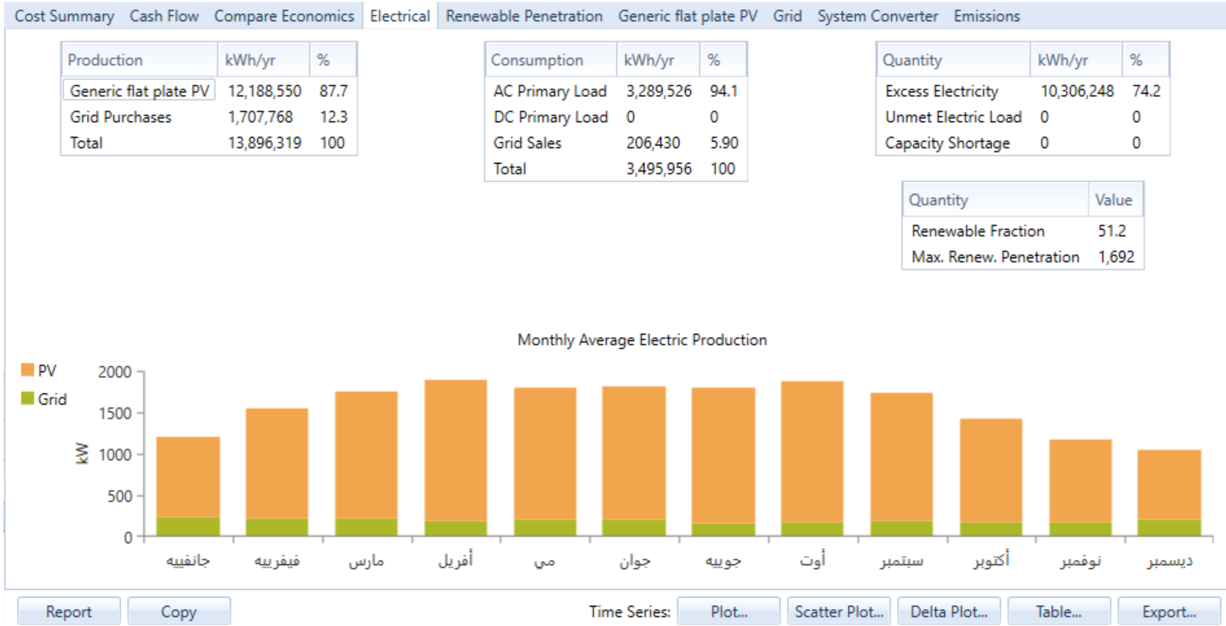


Figure 7. Electricity reltaed flows for the HES without sell back to the grid (First scenario).

Besides, Fig.9 shows cost summary for the HES without selling back to the grid for the First scenario. In addition, renewable energy (solar) contribution for this scenario is presented in Fig.10.

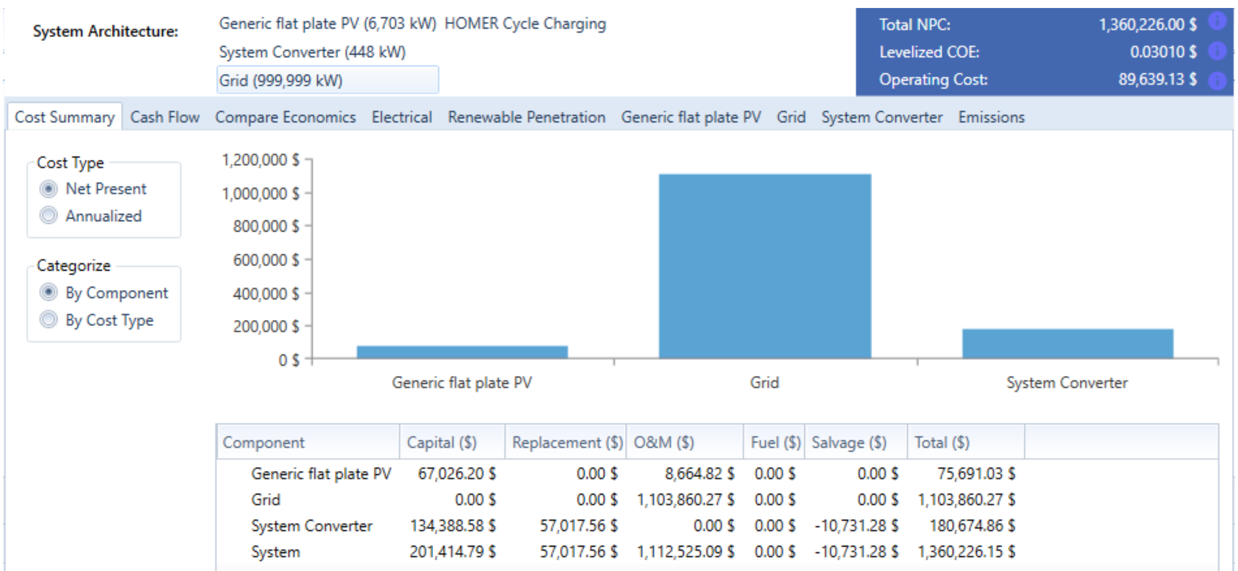
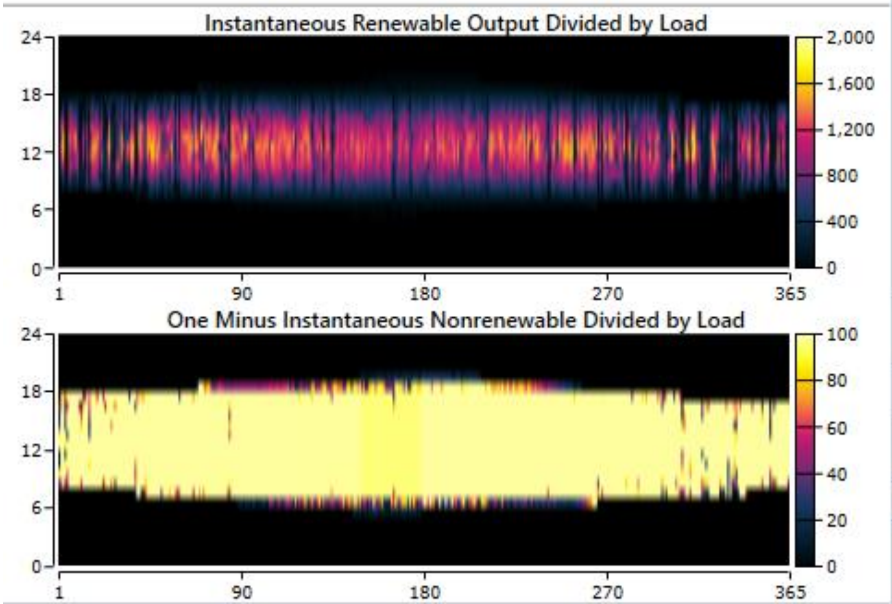


Figure 8. Cost summary for the HES without sell back to the grid (First scenario).

Energy-based metrics	Value	Units
Total renewable production divided by load	349	%
Total renewable production divided by generation	87.7	%
One minus total nonrenewable production divided by load	100	%



Capacity-based metrics	Value	Units
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%

Peak values	Value	Units
Renewable output divided by load (HOMER standard)	1,692	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

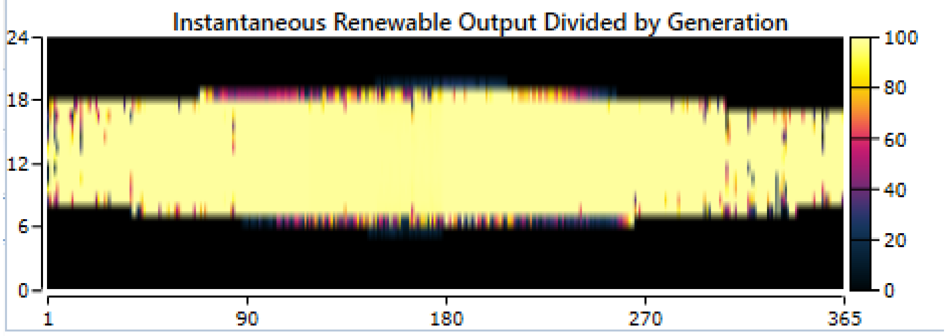


Figure 9. Renewable energy (solar) contribution without sell back to the grid (First scenario).

4.2. The second scenario (current costs with selling back to the grid)

This scenario represents current PV costs by selling back the excess from PV to the grid. The results of the HES configuration and the techno-economic and environment variables related to it are given in Tab.3.

Table 3. The result of HES for the second scenario with selling back to the grid.

Architecture/PV (kW)	Architecture/Grid (kW)	Architecture/Converter (kW)	Architecture/Dispatch
27039	999999	2103	CC
Cost/COE ($/kWh)	Cost/NPC ($)	Cost/Operating cost ($)	Cost/Initial capital ($)
-0.01626709	-2078766	-230520.4	901290
System/Ren Frac (%)	System/Elec Prod (kWh/yr)	System/Elec Cons (kWh/yr)	System/CO2 emissions (kg/yr)
83.86556	5.08E+07	9885090	-3160417
PV/Capital Cost ($)	PV/Production (kWh)	Grid/Energy Purchased (kWh)	Grid/Energy Sold (kWh)
270390	4.92E+07	1594904	6595564

Fig.11 shows the electrical energy flows within the designed HES for the second scenario, including electricity generated by PV, excess electricity, the contribution of the grid as well as the PV among others.

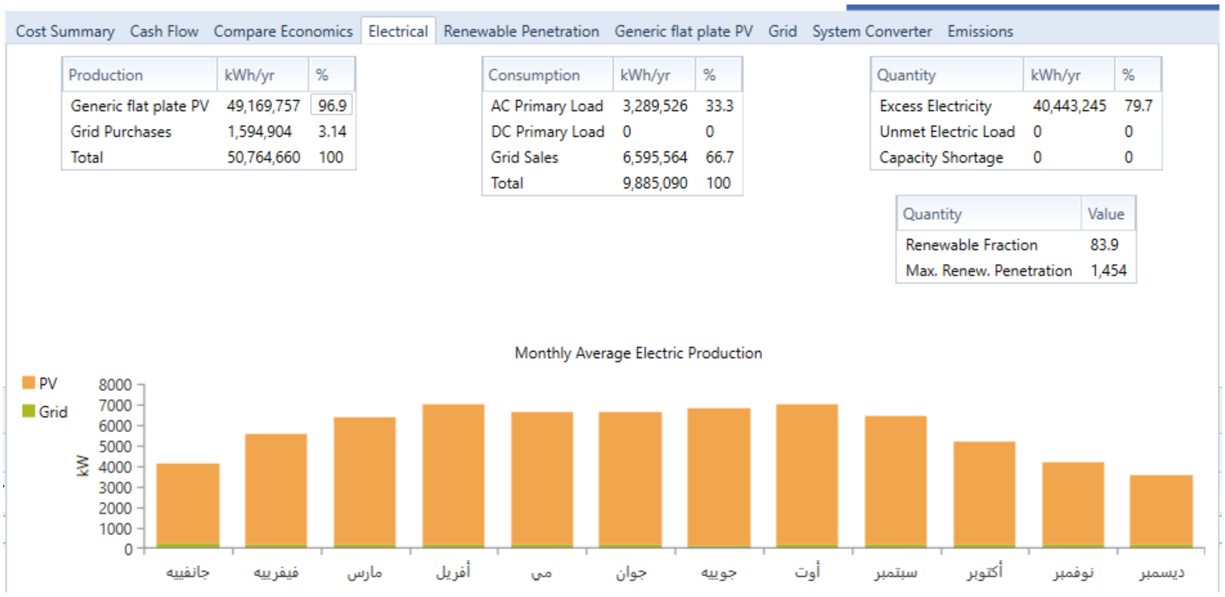


Figure 10. Electricity reltaed flows for the HES without sell back to the grid (First scenario).

Besides, Fig.12 shows cost summary for the HES with selling back to the grid for the First scenario. In addition, renewable energy (solar) contribution for this scenario is presented in Fig.13.

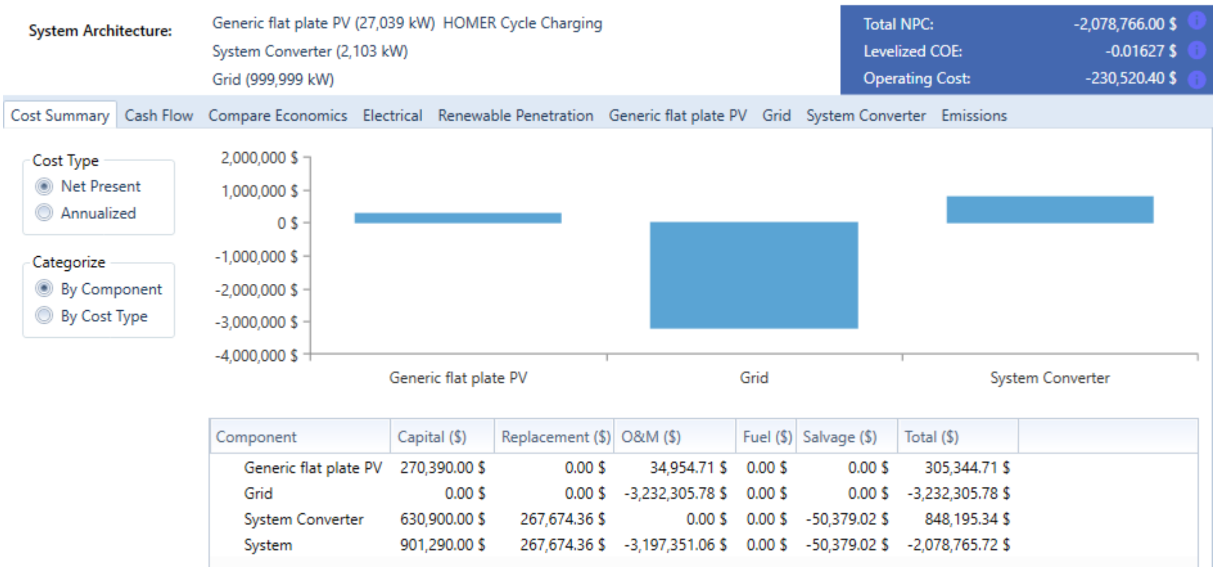
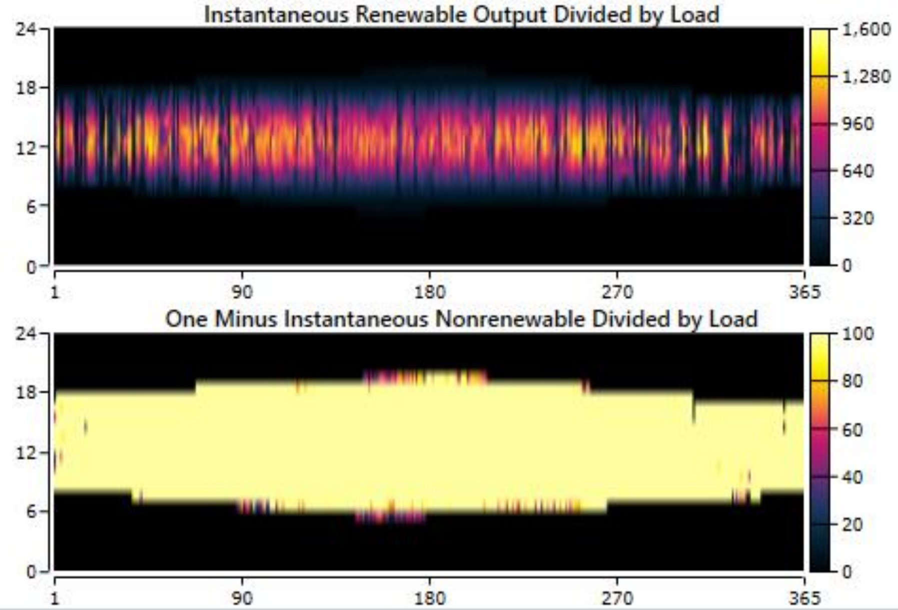


Figure 11. Cost summary for the HES without sell back to the grid (First scenario).

Energy-based metrics	Value	Units
Total renewable production divided by load	497	%
Total renewable production divided by generation	96.9	%
One minus total nonrenewable production divided by load	100	%



Capacity-based metrics	Value	Units
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%

Peak values	Value	Units
Renewable output divided by load (HOMER standard)	1,454	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

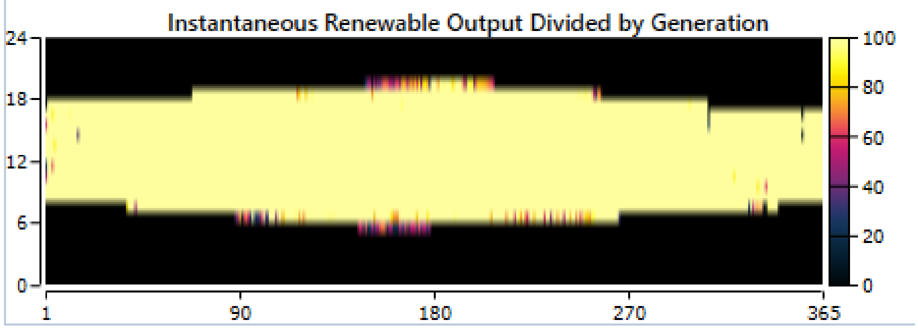


Figure 12. Renewable energy (solar) contribution without sell back to the grid (First scenario).

4.3. The third scenario (projected PV costs without selling back to the grid)

This scenario represents projected PV costs without selling back the excess from PV to the grid. The results of the HES configuration and the techno-economic and environment variables related to it are given in Tab.4.

Table 4. The result of HES for the third scenario without selling back to the grid.

Architecture/PV (kW)	Architecture/Grid (kW)	Architecture/Converter (kW)	Architecture/Dispatch
9555.672392	999999	445.8090427	CC
Cost/COE ($/kWh)	Cost/NPC ($)	Cost/Operating cost ($)	Cost/Initial capital ($)
0.02920843	1320826	88130.23	181521.1
System/Ren Frac (%)	System/Elec Prod (kWh/yr)	System/Elec Cons (kWh/yr)	System/CO2 emissions (kg/yr)
52.19501	1.90E+07	3498021	925079.8
PV/Capital Cost ($)	PV/Production (kWh)	Grid/Energy Purchased (kWh)	Grid/Energy Sold (kWh)
47778.36	1.74E+07	1672229	208494.7

Fig.14 shows the electrical energy flows within the designed HES for the third scenario, including electricity generated by PV, excess electricity, the contribution of the grid as well as the PV among others.

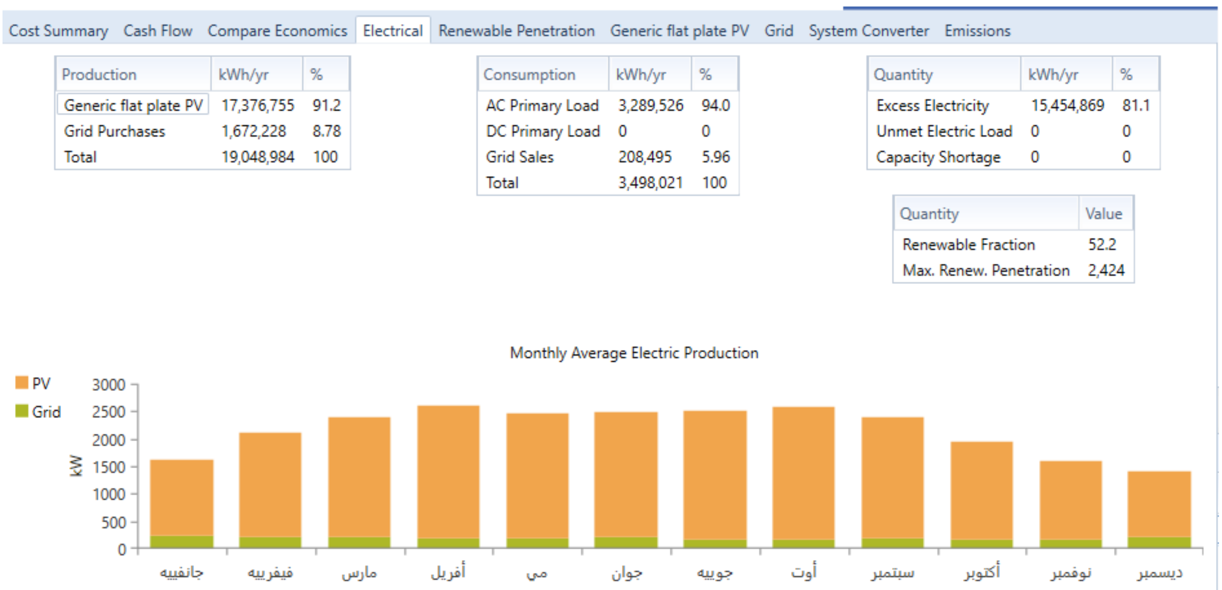
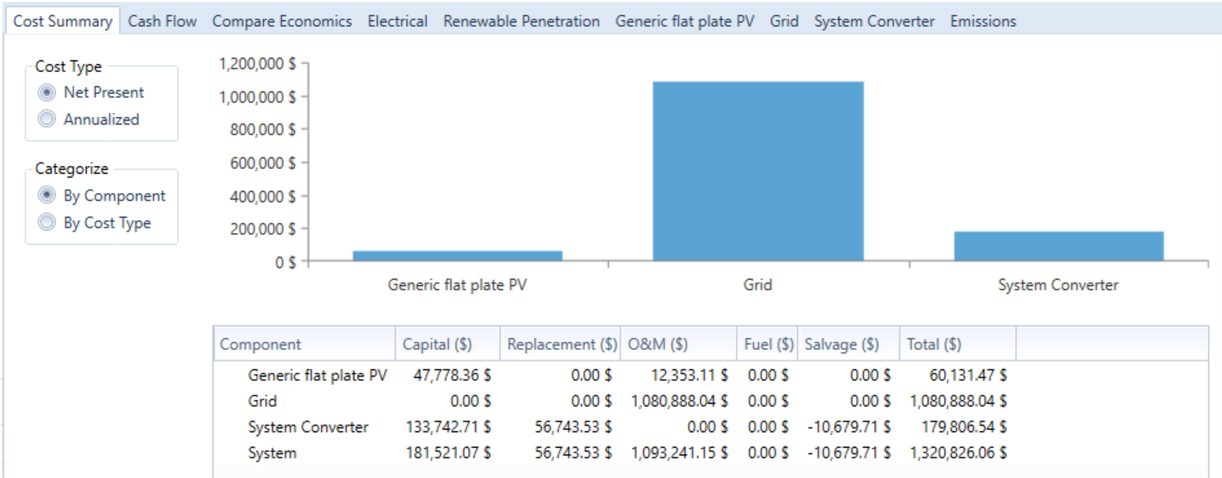


Figure 13. Electricity reltaed flows for the HES without sell back to the grid (First scenario).

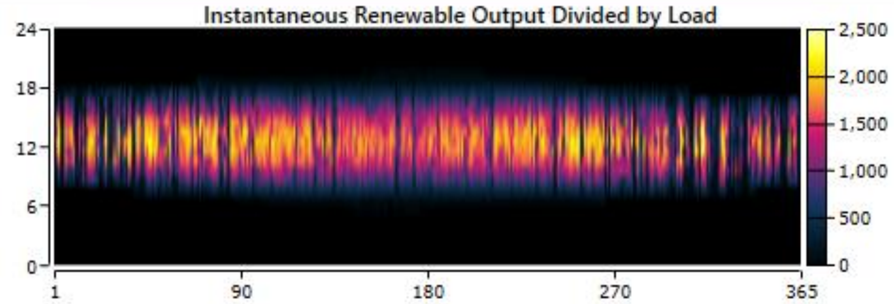
Besides, Fig.15 shows cost summary for the HES without selling back to the grid for the third scenario. In addition, renewable energy (solar) contribution for this scenario is presented in Fig.16.

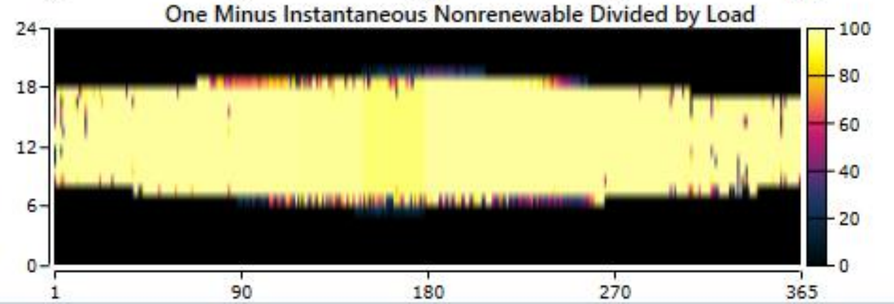


Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic flat plate PV	47,778.36 $	0.00 $	12,353.11 $	0.00 $	0.00 $	60,131.47 $
Grid	0.00 $	0.00 $	1,080,888.04 $	0.00 $	0.00 $	1,080,888.04 $
System Converter	133,742.71 $	56,743.53 $	0.00 $	0.00 $	-10,679.71 $	179,806.54 $
System	181,521.07 $	56,743.53 $	1,093,241.15 $	0.00 $	-10,679.71 $	1,320,826.06 $

Figure 14. Cost summary for the HES without sell back to the grid (First scenario).

Energy-based metrics	Value	Units
Total renewable production divided by load	497	%
Total renewable production divided by generation	91.2	%
One minus total nonrenewable production divided by load	100	%





Capacity-based metrics	Value	Units
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%

Peak values	Value	Units
Renewable output divided by load (HOMER standard)	2,424	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%

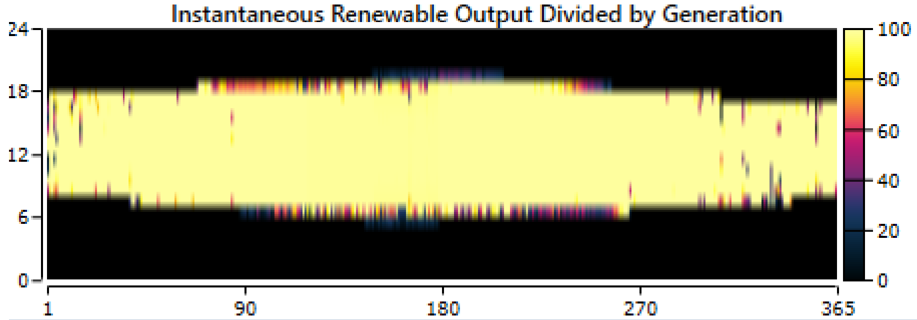


Figure 15. Renewable energy (solar) contribution without selling back to the grid (Third scenario).

Analysis: The results of this scenario indicate that using projected PV costs (based on expected price reductions by 2030) significantly improves the economic viability of the system, even without selling excess electricity back to the grid. The levelized cost of energy (LCOE) is reduced to 0.0292 USD/kWh, which is approximately 42% lower than the average grid electricity tariff for industrial use in Algeria (0.05 USD/kWh). Furthermore, the renewable energy fraction increased slightly compared to the baseline, reaching over 52%, while CO_2 emissions were reduced to approximately 925,000 kg/year. Although the cost reduction is not as dramatic as expected due to the limited scale of the PV component relative to total demand, these results confirm that decreasing PV investment costs alone can contribute significantly to decarbonization and long-term energy savings in desalination applications.

4.4. The fourth scenario (projected PV costs with selling back to the grid)

This scenario represents projected PV costs by selling back the excess from PV to the grid. The results of the HES configuration and the techno-economic and environment variables related to it are given in Tab.5.

Table 5. The result of HES for the fourth scenario by selling back to the grid.

Architecture/PV (kW)	Architecture/Grid (kW)	Architecture/Converter (kW)	Architecture/Dispatch
27039	999999	2103	CC
Cost/COE ($)	Cost/NPC ($)	Cost/Operating cost ($)	Cost/Initial capital ($)
-0.01732504	-2213961	-230520.4	766095
System/Ren Frac (%)	System/Elec Prod (kWh/yr)	System/Elec Cons (kWh/yr)	System/COâ,, (kg/yr)
83.86556	5.08E+07	9885090	-3160417
PV/Capital Cost ($)	PV/Production (kWh)	Grid/Energy Purchased (kWh)	Grid/Energy Sold (kWh)
135195	4.92E+07	1594904	6595564

Fig.17 shows the electrical energy flows within the designed HES for the fourth scenario, including electricity generated by PV, excess electricity, the contribution of the grid as well as the PV among others.

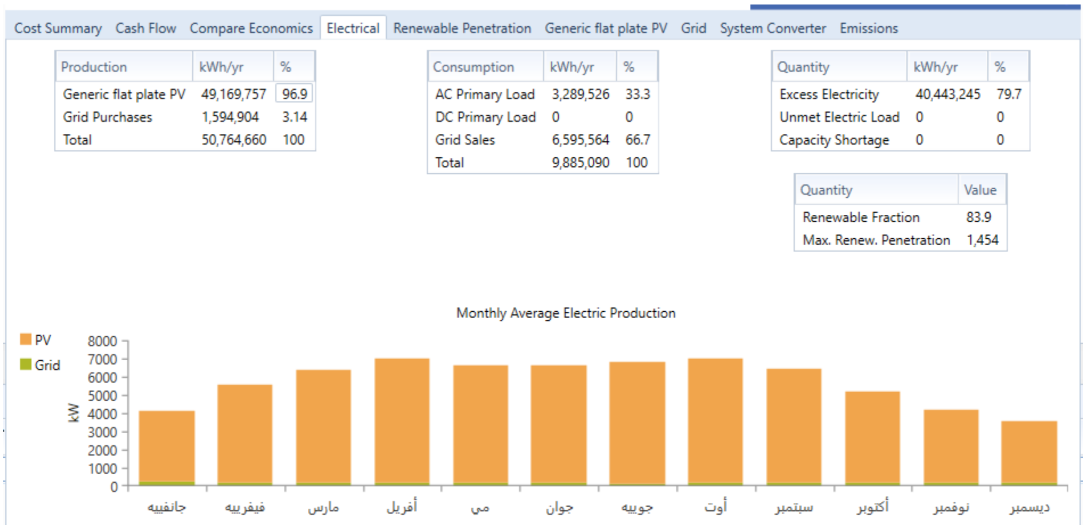


Figure 16. Electricity reltaed flows for the HES by selling back to the grid (Fourth scenario).

Besides, Fig.18 shows cost summary for the HES with selling back to the grid for the Fourth scenario. In addition, renewable energy (solar) contribution for this scenario is presented in Fig.19.

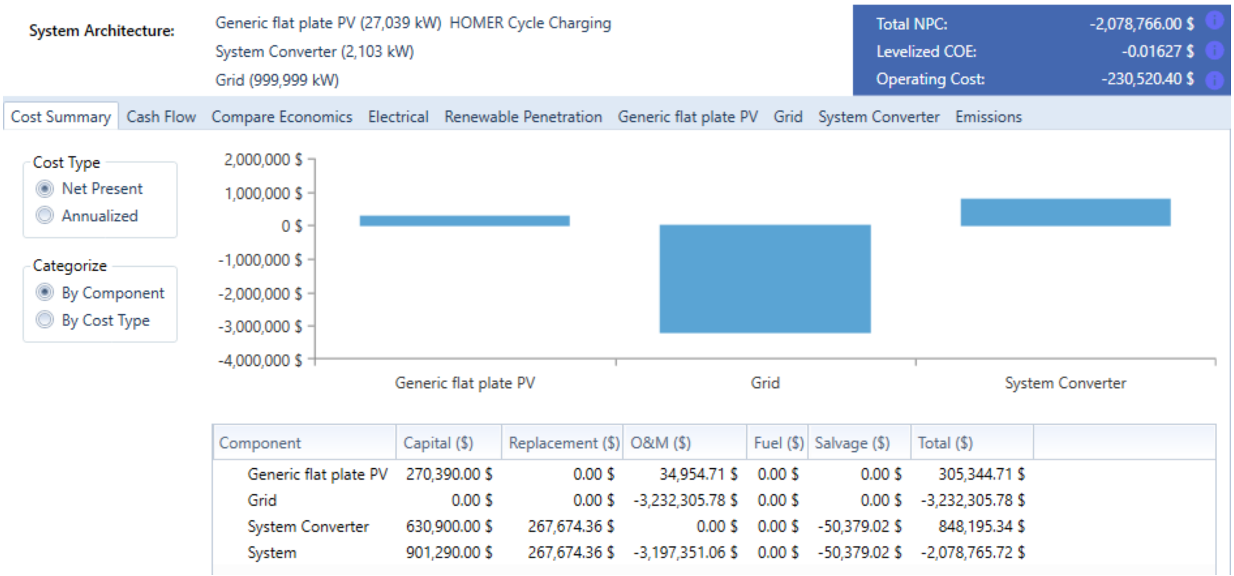
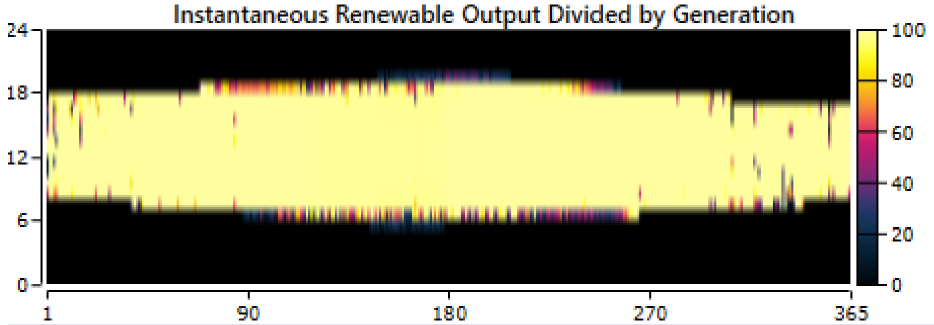


Figure 17. Cost summary for the HES by selling back to the grid (Fourth scenario).

Capacity-based metrics	Value	Units
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%

Peak values	Value	Units
Renewable output divided by load (HOMER standard)	2,424	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%



Energy-based metrics	Value	Units
Total renewable production divided by load	497	%
Total renewable production divided by generation	91.2	%
One minus total nonrenewable production divided by load	100	%

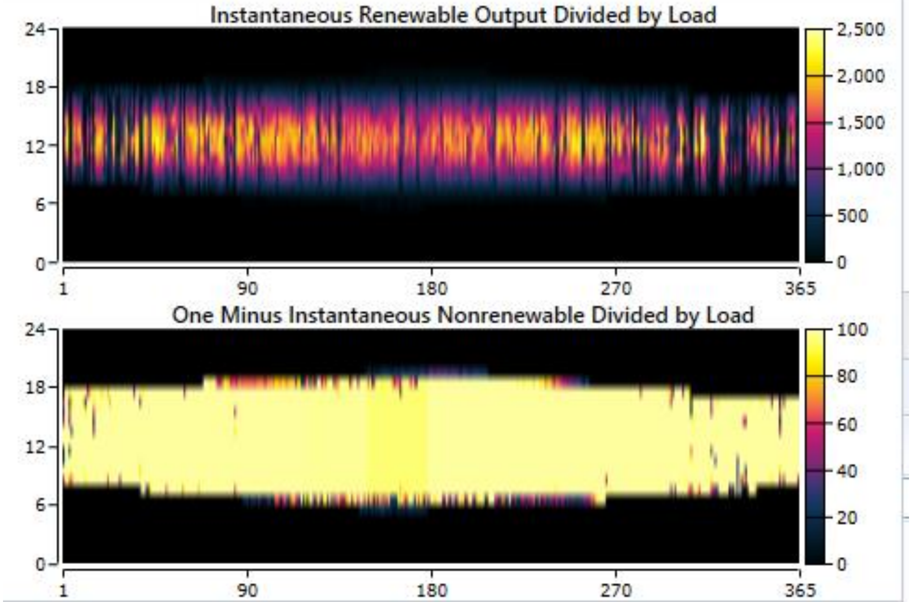


Figure 18. Renewable energy (solar) contribution by selling back to the grid (Fourth scenario).

5. Discussions

The simulation results showed that integrating solar energy can effectively contribute to meeting the energy demand of the desalination plant, especially in an area with high solar radiation like the valley. It is found that with current costs of PV system, and without selling back electricity to the grid, the optimal HES achieved LCOE=0.0301 USD/kWh. However, considering projected costs (in 2030) of PV system, the system archived LCOE=0.029 USD/kWh without selling back to the grid. However, it is not a large difference, even though the costs have dropped by 50%. Compared to electricity prices in Algeria for industrial use (average 0.05 USD/kWh), the obtained LCOE in the current costs is lower, make this HES competitive and viable solution for the unit.

However, when considering selling back to the grid the excess of electricity, the system achieved very cheap costs and achieved a net-positive energy balance, which means LCOE less than 0. However this strategy could be restricted for other barriers mainly, the technical issues related to integrating PV system within existing grid infrastructure and the non-availability of feed in tarif policies for commercial customers.

The proposed renewable based HES (PV+ grid) for water desalination in El Oued is environmentally friendly, economically practical, and technically feasible. Despite obstacles, it offers considerable cost savings and supports Algeria's renewable energy goals, making it a reproducible model for dry places. This strategy can open the door for decarbonized water production in the Sahara and elsewhere with the help of policymakers and advancements in technology.

6. Challenges and Limitations

- **Solar Output Variability**:
  Low production during nights and cloudy days increases grid reliance, highlighting the need for battery storage to enhance reliability.
- **Upfront Costs**:
  Despite long-term viability, the initial capital cost (1,640,925 DZD) may hinder widespread adoption without government subsidies or innovative financing.

7. Comparison with Previous Studies and Recommendations

Results align with similar studies in MENA (e.g., Saudi Arabia, Morocco, and Algeria), where solar-powered desalination reduced water costs to 0.5–1 USD/m3 versus 1.5–2/m³ for conventional systems. Other studies also included energy storage system, improving stability, but increasing costs. In our case, grid reliance lowered costs but limited autonomy. Based on this comparison, we suggest the following recommendations:

- **System Improvements**:
  - Integrate batteries to store surplus energy and reduce grid dependence.
  - Adopt higher PV efficiency or add other renewable energy sources such as biomass and waste to energy within the HES.
- **Policy Support**:
  - Implement feed-in tariffs to incentivize surplus energy sales.
  - Offer tax exemptions or low-interest loans for renewable energy projects in the water sector.
- **Future Research**:
  - Study the impact of sandstorms on PV performance in desert regions.
  - Conduct a full Life Cycle Assessment (LCA) to evaluate the system's environmental footprint.

8. Conclusion

This chapter presented the simulation results and a detailed analysis of four operational scenarios for integrating photovoltaic (PV) solar energy with a large-scale reverse osmosis (RO) desalination plant in El Oued, Algeria. Using HOMER Pro software and real energy consumption data, various hybrid system configurations were assessed in terms of cost, reliability, and environmental impact.

The findings demonstrate that the integration of PV systems can significantly reduce dependence on grid electricity, decrease greenhouse gas emissions, and lower the levelized cost of energy (LCOE), especially when projected future PV costs and electricity selling options are considered. The most economically favorable configuration was achieved under the scenario that combines low PV costs with the ability to sell excess electricity back to the grid, resulting in a negative LCOE and net-positive financial return.

Despite promising results, the analysis also highlighted certain limitations, including variability in solar output, the absence of energy storage in the current design, and policy barriers related to grid feed-in tariffs. These challenges underline the importance of comprehensive regulatory support and further technical improvements to fully realize the benefits of renewable-powered desalination.

Overall, the simulation confirms the technical and economic viability of PV-grid hybrid systems for decarbonizing the desalination sector in southern Algeria, offering a scalable and sustainable solution to address both water and energy security challenges.

Conclusion

This research conducted to evaluate the feasibility of integrating photovoltaic (PV) solar energy systems with reverse osmosis (RO) desalination plants in El Oued region of southern Algeria, within the framework of the national direction towards reducing reliance on fossil fuels, enhancing energy and water security, and minimizing CO2 emissions in the water and energy sectors. A typical RO desalination plant was selected, and real energy consumption data extracted from electricity bills were used, in addition to employing the HOMER Pro software to simulate and analyze the performance of the hybrid system (PV-Grid) in different scenarios for the contribution of renewable energy and based on variation on system costs.

The simulation results showed that integrating solar energy can effectively contribute to meeting the energy demand of the desalination plant, especially in an area with high solar radiation like the valley. It is found that with current costs of PV system, and without selling back electricity to the grid, the optimal HES achieved LCOE=0.0301 USD/kWh. However, considering projected costs (in 2030) of PV system, the system archived LCOE=0.029 USD/kWh without selling back to the grid. However, it is not a large difference, even though the costs have dropped by 50%. Compared to electricity prices in Algeria for industrial use (average 0.05 USD/kWh), the obtained LCOE in the current costs is lower, make this HES competitive and viable solution for the unit.

However, when considering selling back to the grid the excess of electricity, the system achieved very cheap costs and achieved a net-positive energy balance, which means LCOE less than 0. However this strategy could be restricted for other barriers mainly, the technical issues related to integrating PV system within existing grid infrastructure and the non-availability of feed in tarif policies for commercial customers.

The proposed renewable based HES (PV+ grid) for water desalination in El Oued is environmentally friendly, economically practical, and technically feasible. Despite obstacles, it offers considerable cost savings and supports Algeria's renewable energy goals, making it a reproducible model for dry places. This strategy can open the door for decarbonized water production in the Sahara and elsewhere with the help of policymakers and advancements in technology.

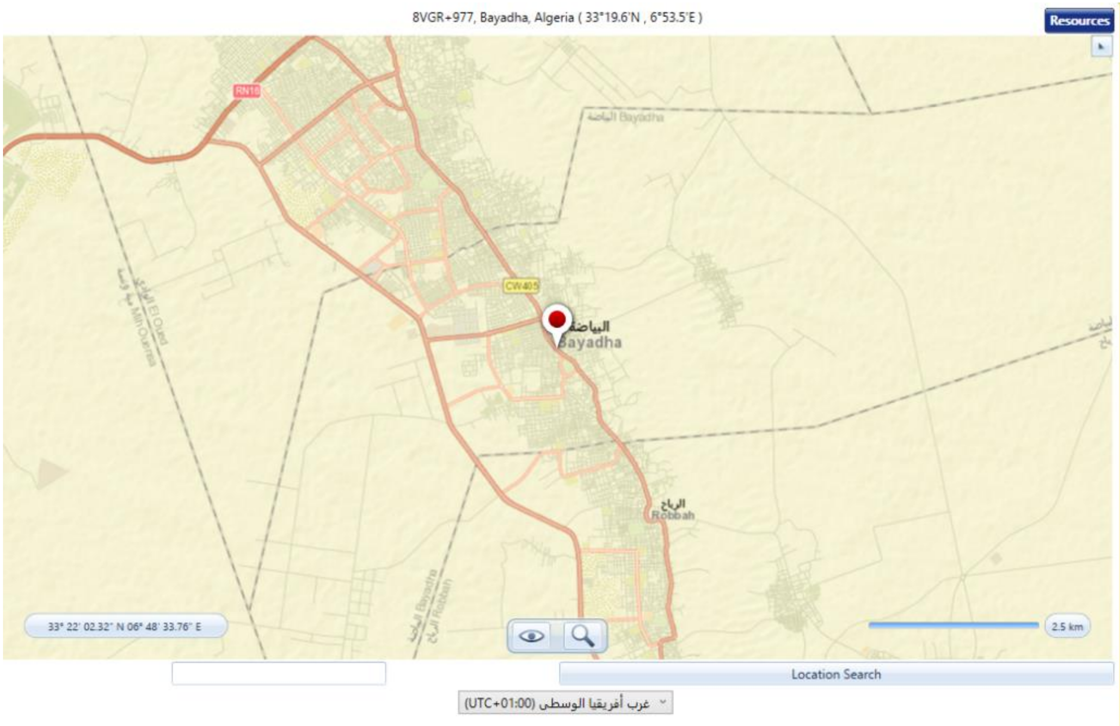
This research concludes that the adoption of solar energy systems in desalination plants in southern Algeria is not only technically feasible but also holds great potential for enhancing energy and water sustainability in the country, specifically when the investment cost of PV is reduced by half by 2030. Therefore, it is recommended to encourage investment initiatives in this field and to provide a regulatory framework that supports the integration of renewable energies within vital facilities such as RO desalination units. As the proposed system can be replicated within large part of the country (Sahara of Algeria), this system can contribute to reduce reliance to fossil fuels and mitigate emissions in the country, which will lead to achieving climate and energy transitions targets. Despite these significant results, various limitations are highlighted including low resolution of datasets (load demand), and uncertainty in costs, which should be considered in future work to provide more accurate decisions.

Appendices

Appendix A List of used software

	Software	Information
1	HOMER Pro	is the global standard for optimizing microgrid design in all sectors, from village power and island utilities to grid-connected campuses and military bases. Originally developed at the National Renewable Energy Laboratory and enhanced and distributed by HOMER Energy.
2	EXCEL	is the industry leading spreadsheet program, a powerful data visualization and analysis tool.

Appendix B Location of the RO desalination unit



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