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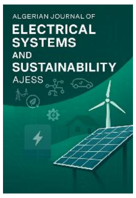

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Green Hydrogen for Irrigation: A Pilot Model for Food Security and Energy Transition in Algeria

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Abstract

This paper presents a pilot model for the integration of solar photovoltaic (PV) energy and green hydrogen production to support irrigation over 100 hectares in Adrar, Algeria. The study focuses on the synergistic relationship between solar radiation, PV generation, and agricultural water demand under desert climatic conditions. Simulation data for the year 2025 demonstrate that hydrogen storage can effectively bridge the temporal mismatch between energy availability and irrigation needs. The results highlight Adrar's potential as a strategic hub for coupling renewable energy and sustainable agriculture in North Africa.

Keywords: Green Hydrogen, Smart Agriculture, PV Energy, Water Management, Energy Transition.

1. Introduction

The challenge of ensuring food security in arid and semi-arid regions increasingly depends on integrated solutions that couple sustainable water management with decarbonized energy supply. Algeria remains highly dependent on cereal imports (notably wheat), exposing its food system to external price and supply shocks and reinforcing the need for resilient domestic production strategies [1,2]. Recent FAO assessments indicate above-average cereal import requirements for Algeria in 2024/25, underscoring persistent vulnerabilities in national food supply [1].
At the same time, Algeria possesses one of the world's most favorable solar resource endowments. Measured daily radiation in parts of the Algerian Sahara frequently exceeds $5–7\ \mathrm{kWh\cdot m^{-2}\cdot day^{-1}}$, while annual solar irradiation can exceed $2300\ \mathrm{kWh\cdot m^{-2}\cdot year^{-1}}$ [3,4]. Such high and stable irradiance makes the Algerian Sahara and the Adrar region particularly attractive for large-scale photovoltaic deployment and renewable hydrogen production [4,5].
Conventional irrigation in Algeria relies heavily on diesel-powered pumping systems, increasing both operating costs and greenhouse gas emissions [6]. Transitioning toward renewable electricity and green hydrogen storage can decouple irrigation from fossil fuels, provide seasonal and daily balancing between PV generation and irrigation demand, and improve energy security in remote agricultural areas [7,8].

1. Decouple irrigation from fossil fuels,
2. Provide temporal balancing between PV generation and irrigation demand, and
3. Enable new uses of hydrogen on farm (e.g., fuel for backup generation or fuel-cell-driven pumps). Recent pilot studies and techno-economic analyses show promising pathways for solar-to-hydrogen systems designed specifically for agricultural irrigation in arid environments.

This paper proposes and evaluates a pilot model for the irrigation of 100 hectares in Adrar that integrates a 10 MWp PV array, alkaline/PEM electrolysis for green hydrogen production, hydrogen storage, and fuel-cell reconversion for on-demand electricity. The modelling framework assesses

(i) seasonal and daily correlations between solar availability and irrigation demand,
(ii) Hydrogen mass balances and storage sizing to cover irrigation peaks,
(iii) System feasibility under Adrar-specific climate inputs. By quantifying the capacity of green hydrogen to bridge the temporal mismatch between PV supply and summer irrigation demand, the study aims to deliver a replicable model for similar arid regions in North Africa and beyond.

2. Methodology

The model integrates a 10 MWp solar PV system, an electrolyzer unit for hydrogen production, and a storage system to ensure continuous energy availability for irrigation pumps and control systems. The hydrogen acts as a long-term storage medium, reconverted into electricity via fuel cells during low-radiation periods. The irrigation demand and energy production were simulated for the entire year 2025 using climate data from Adrar. A comparative analysis was conducted to evaluate seasonal patterns, energy-water correlations, and hydrogen storage performance.

3. System Description

This schematic illustrates the integrated system designed to produce green hydrogen from solar energy for agricultural use, particularly irrigation. The process begins with solar radiation captured by photovoltaic (PV) panels, which convert sunlight into direct current (DC) electricity through the photoelectric effect in semiconductor materials. This conversion efficiency depends on factors such as solar irradiance, panel orientation, temperature, and dust accumulation, which are particularly relevant under desert conditions like those in Adrar, Algeria.

The generated DC power is then conditioned through a power management system that regulates voltage and current to ensure optimal operation of the electrolyzer. The electrolyzer performs water electrolysis, a process in which water (H_2O) molecules are split into hydrogen (H_2) and oxygen (O_2) gases using electrical energy. The overall reaction is [9]:

$$2\,H_2\mathrm{O(l)} \rightarrow 2\mathrm{H_2(g)} + \mathrm{O_2(g)}$$

The electrolysis efficiency is influenced by the electrolyte type (alkaline, PEM, or solid oxide), operating temperature, and cell voltage. In this model, proton exchange membrane (PEM) electrolysis is preferred due to its compactness, fast response, and compatibility with intermittent solar power.

The produced hydrogen gas is then directed into a compression and storage unit, where it is stored in pressurized tanks or solid-state materials (such as metal hydrides). This stored hydrogen serves as a renewable energy carrier, allowing energy decoupling between production and consumption periods. During periods of low solar irradiance or high-energy demand, the hydrogen is fed into a fuel cell or combustion engine to generate electricity or mechanical power for water pumping and irrigation systems [10].

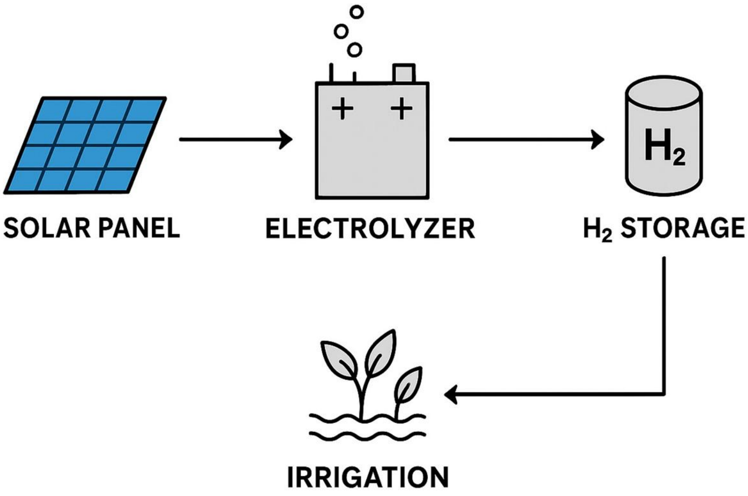

Fig 1. Schematic of a PV-electrolysis hydrogen storage system for irrigation.

4. System modelling and sizing equations (Solar → H_2 → Irrigation)

This section presents the fundamental equations governing the design and sizing of the solar-powered hydrogen production system for agricultural irrigation. The system consists of a photovoltaic (PV) array, an electrolyzer for hydrogen generation, hydrogen storage, and a fuel cell for energy recovery. These equations enable accurate assessment of energy demand, PV production, electrolyzer performance, and overall system efficiency under desert climatic conditions [11].

4.1 Solar Energy Conversion

The solar irradiance incident on the PV surface determines the electrical energy produced. The power output of the PV array is expressed as:

$$P_{pv} = \eta_{PV} \times A_{PV} \times G_T \tag{1}$$

Where:

- P_{pv} is the PV electrical power output (W)
- η_{PV} is the PV conversion efficiency (%)
- A_{PV} is the total PV array area (m²)
- G_T is the solar irradiance on the tilted surface (W/m²)

The PV annual electrical energy (DC to AC after inverter losses) is given by:

$$E_{PV}, yr = P_{PV} \times G_{sun} \times \eta_{inv} \tag{2}$$

If η_{inv} is omitted, use $\eta_{inv} \approx 0.95$ for rough estimates.

4.3 Hydrogen Production by Electrolysis

The hydrogen production rate depends on the electrolyzer efficiency and the supplied electrical power [5,7]:

$$\dot{m}_{H2} = (\eta_{el} \times P_{el} \times t) / (HHV_{H2} * \eta_{fc}) \tag{3}$$

Where:

- ṁ_H2 is the mass flow rate of hydrogen (kg/s)
- η_{el} is the electrolyzer efficiency
- P_{el} is the electrical power supplied (W)
- HHV_{H2} is the higher heating value of hydrogen (39.4 kWh/kg)
- η_{fc} Fuel cell efficiency

4.4 Electrical Energy Available to Electrolyzer

If a fraction f_{H2} of PV energy is devoted to hydrogen production (the remainder covers direct loads, pumping, losses, export), then [5,7]:

$$E_{elect} = f_{H2} \times E_{PV}, yr \tag{4}$$

The annual Hydrogen Mass Production is given by the electrolyzer Specific Energy Consumption (SEC in kWh·kg⁻¹):

$$\boldsymbol{m_{H2} = E_{elect} / SEC} \tag{5}$$

Typical SEC values:

PEM/Alkaline ≈ 45–60 kWh·kg⁻¹ (system level).
The hydrogen produced during daylight hours can be stored in tanks for use during non-solar periods. The energy stored in hydrogen is given by:

$$E_{H2} = \dot{m}_{H2} \times HHV_{H2} \times \eta_{st} \tag{6}$$

Where η_{st} represents the storage efficiency, accounting for compression and thermal losses.

The Hydrogen Reconversion to Electricity (Fuel Cell)
The Annual Electrical energy available from stored hydrogen Reconversion to Electricity (Fuel Cell) is given by :

$$E_{fromH2} = m_{H2} \times LHV_{H2} \times \eta_{fc} \tag{7}$$

This is the useful electricity recovered (kWh·yr⁻¹) to feed pumps, controllers, or night loads.

4.2 Energy Required for Water Pumping

The hydraulic energy required to pump irrigation water depends on the flow rate, total dynamic head, and pump efficiency [12]:

$$E_{pump} = {}^{(\rho \times g \times Q \times H \times t)}\!/_{\eta_{pump}} \tag{8}$$

where:

- ρ is the water density (1000 kg/m³)
- g is the gravitational acceleration (9.81 m/s²)
- Q is the flow rate (m³/s)
- H is the total head (m)
- t is the irrigation duration (s)
- η_{pump}p is the pump efficiency

The Annual pumping energy required to lift water volume V_w through head H:

$$E_{pump} = (\rho \times g \times H \times V_w) \,/\, (\eta_{pump} \times 3600) \ (kWh \cdot yr^{-1}) \tag{9}$$

Where $V_w \ (m^3 \cdot yr^{-1}) = A \times D$ (if D is in m·yr⁻¹ multiply by 10,000 m²/ha or use m³·ha⁻¹·yr⁻¹ directly).

If pumps are driven by fuel cell electricity with efficiencyη_{fc}, hydrogen mass required is:

$$m_{H2}, pump = E_{pump} \,/\, (LHV_{H2} \times \eta_{fc}) \tag{10}$$

Compare m_{H2} ,pump with m_{H2} from production to evaluate sufficiency.

4.3 Electrolyzer Sizing (Power)

The Annual electrical energy for H₂ production:

$$E_{elect,H2} = m_{H2} \times SEC \tag{11}$$

If electrolyzer operates h_{op} hours per year, then:

$$P_{electrolyzer} = \frac{E_{elect,H2}}{h_{op}} (kW) \tag{12}$$

Typical h_{op} values:
Continuous (24/7): $h_{op} = 8760 \, h \cdot yr^{-1}$
Daytime only (≈6 h/day): $h_{op} \approx 2190 \, h \cdot yr^{-1}$

4.4 Storage Sizing

Mass storage needed to cover a target autonomy period (days or energy):

$$V_{stor} = \frac{m_{H2,,req}}{\rho_{H2,stor}} \tag{13}$$

Typical densities:
Compressed H_2 $(200\, bar)$: $\rho \approx 14 - 18 \, kg \cdot m^{-3}$
Liquid H_2: $\rho \approx 70 \, kg \cdot m^{-3}$
Metal hydrides: manufacturer data required.

4.5 Overall System Efficiency

The total system efficiency from solar to usable electrical energy through the hydrogen pathway is given by:

- $\eta_{total} = \eta_{PV} \times \eta_{el} \times \eta_{st} \times \eta_{fc}$ (14)

This equation enables evaluation of the complete energy chain performance, highlighting potential areas for optimization.

3. Results and Discussion

a. Seasonal Solar and Water Demand Correlation

Figure 2 illustrates the normalized seasonal mean values of solar radiation, PV energy, and water consumption. Both solar radiation and PV output peak during spring (~90% of the annual maximum), while water consumption reaches its highest value during summer (~80%). This mismatch demonstrates the necessity of hydrogen storage to ensure continuous irrigation during high-demand periods.

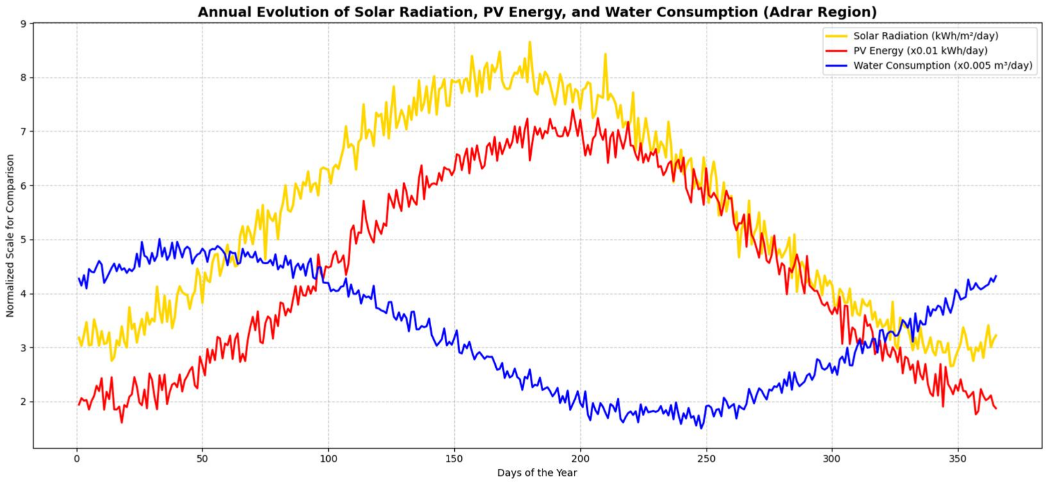

Fig. 2. Seasonal Mean Summary (Normalized %) - Adrar 2025 Simulation.

b. Annual Dynamic Evolution

Figure 3 shows the annual evolution of solar radiation, PV energy, and water consumption. The solar and PV curves demonstrate a consistent increase from winter to summer, while water consumption rises sharply during mid-year, indicating the impact of temperature and evapotranspiration on irrigation demand. Hydrogen production during surplus PV generation can stabilize this imbalance.

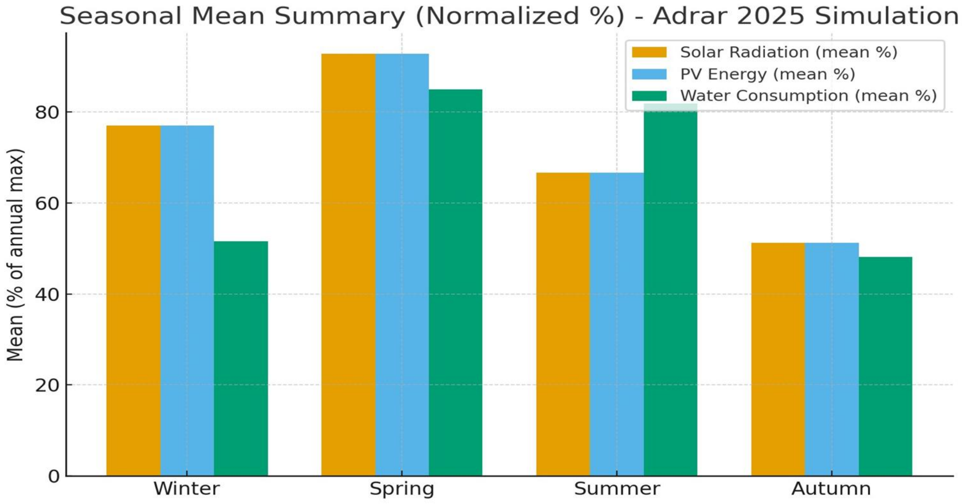

Fig. 3. Annual Evolution of Solar Radiation, PV Energy, and Water Consumption (Adrar Region).

c. Hydrogen and PV Correlation

Figure 4 correlates PV electricity generation with hydrogen production. The hydrogen output follows the solar availability, reaching a maximum of about 700 kg/month in March-April and a minimum of 350 kg/month in late summer. This demonstrates the system's capability to store and redistribute energy seasonally, maintaining irrigation operations even during low PV periods.

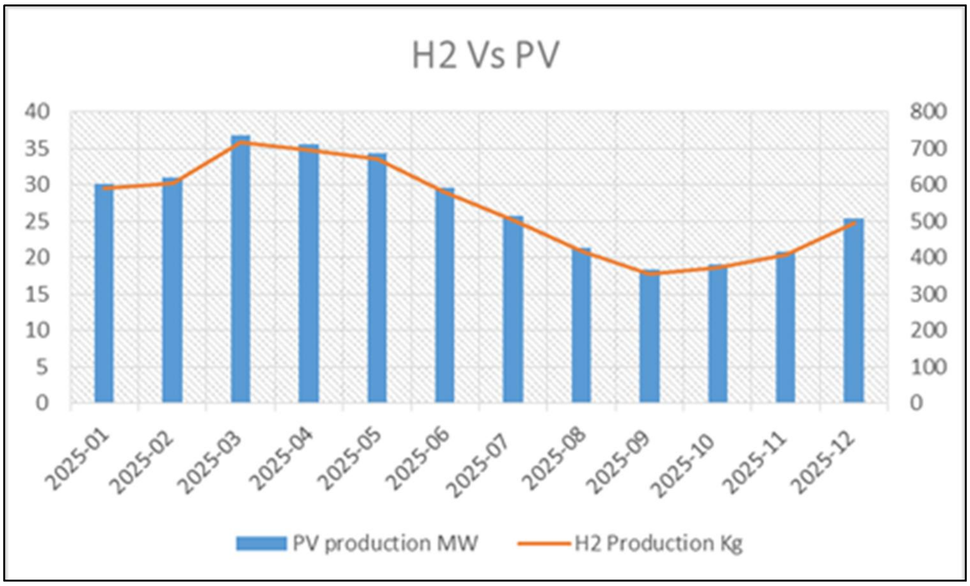

Fig. 4. Monthly Correlation between PV Production and Hydrogen Generation (2025).

5. Comparative Analysis

The Adrar model was compared with other semi-arid regions across the Mediterranean. Results indicate that Adrar's annual solar irradiance exceeds 2300 kWh/m², allowing for a PV yield of around 1700 kWh/kWp/year and a hydrogen production potential of 18–20 kg/day per MWp. Compared to Southern Italy and Tunisia, Adrar offers higher stability and scalability for renewable-based agriculture.

Table 1. Comparison of solar resource potential, photovoltaic yield, and hydrogen production capacity in selected Mediterranean and Saharan regions

Region	Solar Potential (kWh/m²/year)	Avg. PV Yield (kWh/kWp/year)	H_2 Production Potential (kg/day per MWp)	Remarks
Adrar (Algeria)	2300–2500	1700	18–20	High solar stability, ideal for hydrogen storage
M'Sila (Algeria)	2100	1550	16–18	Moderate solar resource, suitable for small-scale hydrogen
Tunisian Sahara	2400	1750	19–21	Similar to Adrar, strong hydrogen potential
Southern Italy	2000	1450	14–16	Lower solar input, but higher energy efficiency

Adrar thus emerges as an optimal site for large-scale green hydrogen–agriculture coupling, due to its stable solar irradiance, low humidity, and availability of flat desert land.

6. Conclusion

This work has presented a comprehensive analysis of a solar-powered hydrogen irrigation model designed for a 100-hectare pilot farm in Adrar, Algeria. The results confirm that integrating photovoltaic generation, water electrolysis, and hydrogen-based energy storage can provide a technically viable and environmentally sustainable solution for agricultural electrification in remote arid regions. The developed framework ensures a continuous and autonomous energy supply for irrigation while minimizing greenhouse gas emissions and dependence on fossil resources.

Beyond its technical feasibility, this model contributes to the broader objectives of energy transition and climate resilience in the agricultural sector. Hydrogen serves as both a storage medium and an enabler for decoupling water pumping from solar intermittency, enhancing operational reliability throughout the year. The study also demonstrates that the combination of renewable generation and green hydrogen can serve as a cornerstone for future smart farming systems in North Africa, particularly when coupled with digital control, AI-based water management, and advanced monitoring platforms.

Future research should focus on optimizing the hydrogen production–storage–utilization chain through real-time data integration, cost reduction strategies, and hybrid system optimization. Moreover, large-scale demonstrations and multi-sectoral collaborations are recommended to validate the long-term economic viability and policy relevance of hydrogen-assisted irrigation in semi-arid and desert environments.

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Annex

Worked Numerical — 100 ha Pilot_Adrar

Assumptions:

- Area A = 100 ha
- Annual irrigation demand $D = 3{,}000\, m^3 \cdot ha^{-1} \cdot yr^{-1} \Rightarrow V\_w = 300{,}000\, m^3 \cdot yr^{-1}$

- Hydraulic head $H = 20\,m$
- Pump efficiency $\eta_{pump} = 0.60$
- PV capacity $P_{PV} = 10\,MWp = 10{,}000\,kWp$
- PV yield $G_{sun} = 1{,}700\,kWh \cdot kWp^{-1} \cdot yr^{-1}\,(Adrar\ typical)$
- Inverter efficiency $\eta_{inv} = 0.95$
- Fraction $f_{H2} = 1.0$
- Electrolyzer $SEC = 50\,kWh \cdot kg^{-1}$
- Fuel cell efficiency $\eta_{fc} = 0.50$
- $LHV_{H2} = 33.3\,kWh \cdot kg^{-1}$

Step 1 — PV annual energy

$E_{PV,yr} = 10{,}000 \times 1{,}700 \times 0.95 = 16{,}150{,}000\,kWh \cdot yr^{-1}$

Step 2 — Annual pumping energy

$E_{pump} = (1000 \times 9.81 \times 20 \times 300{,}000) / (0.60 \times 3600) = 27{,}250{,}000\,kWh \cdot yr^{-1}$

Step 3 — H₂ mass required to cover pumping (via fuel cell)

$m_{H2,pump} = 27{,}250{,}000 / (33.3 \times 0.50) \approx 1{,}636{,}637\,kg \cdot yr^{-1}$

Step 4 — Electrical energy to produce that H₂

$E_{elect,H2} = 1{,}636{,}637 \times 50 = 81{,}831{,}850\,kWh \cdot yr^{-1}$

Step 5 — Comparison

PV energy available (~16.15 GWh·yr^{-1}) << Electrolyzer demand (~81.83 GWh·yr^{-1}): PV capacity insufficient.

Step 6 — Electrolyzer power sizing

If daytime only (2190 h): $P_{electrolyzer} \approx 37.4\,MW$
If continuous (8760 h): $P_{electrolyzer} \approx 9.35\,MW$

Step 7 — Storage volume (compressed at 200 bar)

Monthly autonomy: $m_{H2,month} = 1{,}636{,}637 / 12 \approx 136{,}387\,kg$
At $\rho_{H2,stor} \approx 15\,kg \cdot m^{-3} \rightarrow V\_stor \approx 9{,}093\,m^3$

Biography

Hocine Belmili is a Senior Researcher and Director of Research at the Unit for the Development of Solar Equipment (UDES), under the Renewable Energy Development Center (CDER), Algeria. He holds extensive expertise in renewable energy systems, micro-grids, smart grids, and sustainable urban energy solutions. His research focuses on the integration of solar PV, wind, hydrogen, and hybrid energy systems for both urban and rural applications, with particular emphasis on agriculture, smart cities, and resilient infrastructures.

Over the years, Dr. Belmili has contributed to several international and national projects on micro-grid optimization, smart farming, and sustainable energy transition, addressing energy access in remote areas, decarbonization of agriculture, and digital innovations such as IoT, AI, and digital twins for energy management. He has also coordinated collaborations between Algeria, Europe, and the Mediterranean region within frameworks such as Interreg, Horizon, and Next Med programmes.

His publication record spans peer-reviewed journals, conferences, and book chapters covering topics like hybrid renewable systems, smart micro-grids for agriculture, and energy efficiency in urban contexts. Dr. Belmili is actively engaged in capacity building, supervision of master's and PhD students, and knowledge transfer in the field of sustainable energy.

Beyond academia, his work aims to bridge technological innovation and socio-economic development, promoting energy equity, climate resilience, and sustainable urbanization in line with the UN Sustainable Development Goals (SDGs). **E-mail:** , hocine.belmili78@gmail.com / h.belmili@cder.dz/hocine.belmili@atrst.dz