

REPUBLIQUE ALGERIENNE DEMOCRATIQUE ET POPULAIRE

Ministère de l'enseignement supérieur et de la recherche scientifique

Ecole Nationale Polytechnique



Département d'Electrotechnique

End-of-study project dissertation

for obtaining the State Engineer's degree in Electrical Engineering

Option : Hydrogen Technology

Study and design of a decentralized green ammonia production system from renewable hydrogen for agricultural applications

M. AIT MESSAOUD Elias

Under the supervision of : **Pr. BELMILI Hocine** and **Dr. TURAN Volkan**

Presented and defended publicly on 30/06/2026

Composition of the jury :

|               |                     |                |
|---------------|---------------------|----------------|
| President     | Dr. TADJINE Soumaya | ENP            |
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| Co-supervisor | Dr. TURAN Volkan    | Tillia Company |
| Examiner      | Dr. MAAMRI Rachid   | ENP            |



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Département Electrotechnique

Mémoire de projet de fin d'études

Pour l'obtention du diplôme d'ingénieur d'état en Electrotechnique

Option : Technologie de l'hydrogène

Etude et conception d'un système de production décentralisée d'ammoniac vert à partir d'hydrogène renouvelable pour une application agricole

M. AIT MESSAOUD Elias

Sous la direction du **Pr. BELMILI Hocine** et du **Dr. TURAN Volkan**

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## الملخص :

في ظل التحديات الطاقوية والمناخية الراهنة، يبرز الأمونيا الأخضر كمسار واعد لإزالة الكربون من القطاع الزراعي. تدرس هذه الدراسة وتصمم نظامًا لامركزيًا لإنتاج الأمونيا الأخضر مدعومًا بالطاقة الشمسية الكهروضوئية. وتم تطوير نموذج رقمي متكامل يشمل التحليل الكهربائي بغشاء تبادل البروتونات PEM، وتخزين الهيدروجين H<sub>2</sub>، واصطناع هابر-بوش (ودمج في منصة تفاعلية مطورة ببرمجيات Python, Dash, Plotly)، مما يتيح محاكاة ورصدًا فوريًا للأداء عبر كافة الولايات الجزائرية الـ 58. يتضمن التحليل التقني-الاقتصادي حساب النفقات الرأسمالية (CAPEX)، والنفقات التشغيلية (OPEX)، وتكلفة المياه، والتكلفة المستوية للأمونيا (LCOA) وقد أجريت دراسة مقارنة بين ثلاث ولايات (الجلفة، تيبازة، وأدرار)؛ حيث سجلت ولاية الجلفة أعلى معدل إنتاج وأقل تكلفة مستوية، في حين شهدت ولاية أدرار خسائر في الإنتاج نتيجة لارتفاع درجات الحرارة وتراكم الغبار. وتعد هذه المنصة أداة فعالة لدعم اتخاذ القرار وتحديد المواقع المثلى لإنشاء وحدات إنتاج الأمونيا الأخضر محليًا.

**الكلمات المفتاحية :** الأمونيا الأخضر، الهيدروجين الأخضر، التحليل الكهربائي (PEM)، الطاقة الشمسية الكهروضوئية، الزراعة المستدامة، عملية هابر-بوش، التكلفة المستوية للأمونيا (LCOA)، المحاكاة التفاعلية.

## Résumé :

Face aux défis énergétiques et climatiques, l'ammoniac vert offre une voie prometteuse pour décarboner l'agriculture. Ce projet étudie et conçoit un système décentralisé de production d'ammoniac vert à partir d'énergie solaire photovoltaïque. Un modèle numérique intégré (électrolyse PEM, stockage H<sub>2</sub>, synthèse Haber-Bosch) est implémenté dans une plateforme interactive (Python, Dash, Plotly) permettant de visualiser en temps réel les performances pour les 58 wilayas algériennes. L'analyse technico-économique inclut CAPEX, OPEX, coût de l'eau et LCOA. Trois wilayas (Djelfa, Tipaza, Adrar) sont comparées : Djelfa montre la meilleure production et le LCOA le plus bas, tandis qu'Adrar subit des pertes dues à la chaleur et aux poussières. La plateforme constitue un outil d'aide à la décision pour l'implantation locale d'unités d'ammoniac vert.

**Mots-clés :** Ammoniac vert, hydrogène vert, électrolyse PEM, solaire photovoltaïque, agriculture durable, Haber-Bosch, LCOA, simulation interactive.

## Abstract

Facing energy and climate challenges, green ammonia offers a promising pathway to decarbonise agriculture. This project studies and designs a decentralised green ammonia production system powered by solar photovoltaic energy. An integrated numerical model (PEM electrolysis, H<sub>2</sub> storage, Haber-Bosch synthesis) is implemented in an interactive platform (Python, Dash, Plotly) enabling real-time visualisation of performance for all 58 Algerian wilayas. The techno-economic analysis includes CAPEX, OPEX, water cost, and LCOA. Three wilayas (Djelfa, Tipaza, Adrar) are compared: Djelfa shows the highest production and lowest LCOA, while Adrar suffers losses due to heat and dust. The platform serves as a decision-support tool for siting local green ammonia units.

**Keywords:** Green ammonia, green hydrogen, PEM electrolysis, solar PV, sustainable agriculture, Haber-Bosch, LCOA, interactive simulation.

# Contents

## List of figures

## List of tables

## List of acronyms

## List of symbols

|                           |    |
|---------------------------|----|
| General introduction..... | 13 |
|---------------------------|----|

|                                    |    |
|------------------------------------|----|
| CHAPTER 1 : LITERATURE REVIEW..... | 16 |
|------------------------------------|----|

|                                                                                        |    |
|----------------------------------------------------------------------------------------|----|
| 1.1 Introduction .....                                                                 | 16 |
| 1.2 Ammonia production methods.....                                                    | 17 |
| 1.2.1 Conventional Ammonia Production via Steam Methane Reforming (Grey Ammonia) ..... | 17 |
| 1.2.2 Ammonia Production with Carbon Capture and Storage (Blue Ammonia).....           | 18 |
| 1.2.3 Green Ammonia Production .....                                                   | 18 |
| 1.3 Current Status of Ammonia .....                                                    | 18 |
| 1.3.1 Global Overview .....                                                            | 18 |
| 1.3.2 The Situation in Algeria.....                                                    | 19 |
| 1.4 The Status of Green Hydrogen .....                                                 | 20 |
| 1.4.1 Global Overview .....                                                            | 20 |
| 1.4.2 In Algeria.....                                                                  | 21 |
| 1.5 Installed Photovoltaic (PV) Capacity in Algeria.....                               | 23 |
| 1.6 Water Resources in Algeria.....                                                    | 23 |
| 1.7 Decentralized Green Ammonia Production from Photovoltaics .....                    | 24 |
| 1.7.1 Electrolyzer Technologies .....                                                  | 24 |
| 1.7.2 Hydrogen Storage.....                                                            | 26 |

|                            |    |
|----------------------------|----|
| CHAPTER 2 : MODELING ..... | 29 |
|----------------------------|----|

|                                                               |    |
|---------------------------------------------------------------|----|
| 2.1 Model Assumptions .....                                   | 29 |
| 2.2 Solar Resource and Photovoltaic Generation Modeling ..... | 29 |
| 2.2.1 Input Data Configuration per Wilaya .....               | 29 |
| 2.2.2 Clear Sky Model.....                                    | 30 |
| 2.2.3 Irradiance on a Tilted Surface.....                     | 31 |
| 2.2.4 PV Cell Thermal Model .....                             | 31 |
| 2.2.5 Output Power $P(t)$ .....                               | 32 |
| 2.3 Modeling of PEM Electrolyser .....                        | 33 |
| 2.4 Modeling of Hydrogen Storage .....                        | 34 |

|                                                                       |    |
|-----------------------------------------------------------------------|----|
| 2.4.1 Role of the Storage Tank in the Process .....                   | 34 |
| 2.4.2 Storage Management Logic.....                                   | 34 |
| 2.5 Modeling of Ammonia Synthesis (Haber-Bosch).....                  | 34 |
| 2.6 Techno-Economic Modeling.....                                     | 35 |
| 2.6.1 Cost Structure .....                                            | 35 |
| 2.6.2 LCOA calculation .....                                          | 36 |
| <br>CHAPTER 3 : DEVELOPMENT OF THE INTERACTIVE SIMULATION PLATFORM .. | 38 |
| 3.1 Introduction .....                                                | 38 |
| 3.2 Platform architecture .....                                       | 38 |
| 3.3 Windows presentation.....                                         | 39 |
| 3.3.1 Process diagram Tab.....                                        | 39 |
| 3.3.2 PV model Sub-Panel.....                                         | 40 |
| 3.3.3 PEM Electrolyser Sub-Panel .....                                | 41 |
| 3.3.4 Agricultural application .....                                  | 41 |
| 3.3.5 History Tab .....                                               | 42 |
| 3.3.6 Map Tab.....                                                    | 42 |
| 3.3.7 Economy Tab.....                                                | 43 |
| <br>CHAPTER 4 : STUDY CASE .....                                      | 45 |
| 4.1 System Configuration .....                                        | 45 |
| 4.2 Results .....                                                     | 45 |
| 4.3 Discussion.....                                                   | 46 |
| 4.4 Sensitivity Analysis – Impact of PV Peak Power .....              | 47 |
| 4.5 Conclusion .....                                                  | 49 |
| 4.6 General conclusion .....                                          | 50 |
| <br>Bibliography.....                                                 | 52 |
| <br>APPENDICES .....                                                  | 55 |
| Appendix A.....                                                       | 55 |
| Data wilaya information.....                                          | 55 |
| Appendix B.....                                                       | 56 |
| Tools and technologies .....                                          | 56 |
| Appendix C.....                                                       | 57 |
| Wilaya’s results – Situation 1 : .....                                | 57 |
| Wilaya’s results – Situation 2 : .....                                | 58 |

## **List of figures**

- 1.1 Ammonia production process
- 1.2 Global ammonia production in the world
- 1.3 Hydrogen in the world
- 1.4 Solar radiation in Algeria
- 1.5 Projected National Megawatt Capacity and Current progress
- 1.6 Green ammonia value chain
- 1.7 Advantages and disadvantages of Electrolysis types
- 1.8 SWOT of hydrogen storage
  
- 3.1 The MVC structure
- 3.2 General Web application Flowchart
- 3.3 Process diagram Tab
- 3.4 PV model Sub-Panel
- 3.5 PEM Electrolyser Sub-Panel
- 3.6 Agricultural application Sub-Panel
- 3.7 History Tab
- 3.8 Map Tab
- 3.9 Economy Tab
  
- B.1 Technical specification

## **List of tables**

1.1 Estimated Probable Hydrogen Production Rate by CDER (1992–1996)

1.2 Characteristics of electrolysis technologies

1.3 Electrode chemical equations

1.4 Materials for solid-state storage of hydrogen

2.1 Cost structure

2.2 Cost values

3.1 Process diagram configuration

3.2 PV model sub-panel configuration

3.3 PEM electrolyser sub-panel configuration

3.4 Alarm system (trigger conditions)

3.5 Agricultural application configuration

3.6 History tab configuration

3.7 Map tab configuration

3.8 Economy tab configuration

4.1 System configuration – Situation 1

4.2 Cost configuration – Situation 1

4.3 Results – Situation 1

4.4 System configuration – Situation 2

4.5 Cost configuration – Situation 2

4.6 Results – Situation 2

4.7 Impact of PV Peak Power on Ammonia production

4.8 Impact of PV Peak Power on LCOA

A.1 Data wilaya information

C.1 Full results for all 58 wilayas – Situation 1

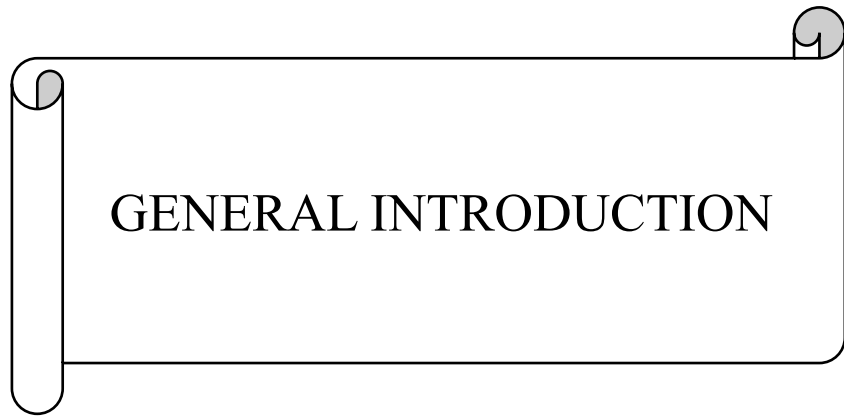
C.2 Full results for all 58 wilayas – Situation 2

## List of acronyms

|                 |                                                              |
|-----------------|--------------------------------------------------------------|
| AEL             | Alkaline Electrolyser                                        |
| ASU             | Air Separation Unit                                          |
| CAPEX           | Capital Expenditure                                          |
| CCS             | Carbon Capture and Storage                                   |
| CDER            | Centre de Développement des Énergies Renouvelables (Algeria) |
| CPI             | Consumer Price Index                                         |
| DA              | Algerian Dinar                                               |
| IEA             | International Energy Agency                                  |
| KPI             | Key Performance Indicator                                    |
| LCOA            | Levelised Cost of Ammonia                                    |
| MOF             | Metal-Organic Framework                                      |
| MVC             | Model-View-Controller                                        |
| NH <sub>3</sub> | Ammonia                                                      |
| NOCT            | Nominal Operating Cell Temperature                           |
| O&M             | Operation and Maintenance                                    |
| OPEX            | Operational Expenditure                                      |
| PEM             | Proton Exchange Membrane                                     |
| PSA             | Pressure Swing Adsorption                                    |
| PV              | Photovoltaic                                                 |
| RO              | Reverse Osmosis                                              |
| SMR             | Steam Methane Reforming                                      |
| SOEC            | Solid Oxide Electrolyser Cell                                |
| STC             | Standard Test Conditions                                     |
| SWOT            | Strengths, Weaknesses, Opportunities, Threats                |
| WGS             | Water-Gas Shift                                              |
| WWTP            | Wastewater Treatment Plant                                   |

## List of symbols

| Symbol                       | Description                                                     | Unit                        |
|------------------------------|-----------------------------------------------------------------|-----------------------------|
| $A_0, A_1, K$                | Hottel model coefficients                                       | –                           |
| $b$                          | Angular parameter for equation of time                          | deg                         |
| $B_{0h}$                     | Direct horizontal irradiance                                    | W/m <sup>2</sup>            |
| $C_{total}$                  | Total CAPEX                                                     | €                           |
| $C_{tank}$                   | Hydrogen storage capacity                                       | kg                          |
| $D_{0h}$                     | Diffuse horizontal irradiance                                   | W/m <sup>2</sup>            |
| $E_{sp}$                     | Specific energy consumption (electrolyser)                      | kWh/kg H <sub>2</sub>       |
| $E_{sp,eff}$                 | Effective specific energy at part-load                          | kWh/kg H <sub>2</sub>       |
| $ET$                         | Equation of time                                                | minutes                     |
| $f_{dust}$                   | Soiling (dust) factor                                           | –                           |
| $F$                          | Faraday constant                                                | 96485 C/mol                 |
| $G_0$                        | Solar constant (1367 W/m <sup>2</sup> )                         | W/m <sup>2</sup>            |
| $G_e$                        | Extraterrestrial irradiance                                     | W/m <sup>2</sup>            |
| $G_{0h}$                     | Global horizontal irradiance                                    | W/m <sup>2</sup>            |
| $G_{\beta}$                  | Global tilted irradiance                                        | W/m <sup>2</sup>            |
| $h_s$                        | Solar altitude angle                                            | deg                         |
| $L_{loc}$                    | Longitude of the location                                       | deg                         |
| $M_{H_2}, M_{N_2}, M_{NH_3}$ | Molar mass of H <sub>2</sub> , N <sub>2</sub> , NH <sub>3</sub> | 2.016, 28.014, 17.031 g/mol |
| $\dot{m}_{H_2}$              | Hydrogen mass flow rate                                         | kg/h                        |
| $\dot{m}_{demand}$           | Hydrogen flow rate demand                                       | kg/h                        |
| $N_2$                        | Nitrogen                                                        | –                           |
| $N_j$                        | Day number of the year                                          | –                           |
| NOCT                         | Nominal Operating Cell Temperature                              | °C                          |
| $O_{total}$                  | Total annual OPEX                                               | €/year                      |
| $P_{peak}$                   | Peak PV power                                                   | kW                          |
| $P_{EL}$                     | Nominal electrolyser power                                      | kW                          |
| $P_{elec}$                   | Electrical power consumed by electrolyser                       | kW                          |
| $P_{PV}$                     | PV output power                                                 | kW                          |
| $Q_{NH_3}$                   | Annual ammonia production                                       | kg/year or t/year           |
| $r$                          | Discount rate                                                   | %                           |
| $R$                          | Universal gas constant                                          | 8.314 J/(mol·K)             |
| $R_b$                        | Geometric tilt factor for direct radiation                      | –                           |
| $T$                          | Absolute temperature                                            | K                           |
| $T_{amb}$                    | Ambient temperature                                             | °C                          |
| $T_{cell}$                   | PV cell temperature                                             | °C                          |
| $T_{STC}$                    | STC reference temperature (25°C)                                | °C                          |
| $V_{cell}$                   | Electrolyser cell voltage                                       | V                           |
| $V_{nom}$                    | Nominal cell voltage                                            | V                           |
| $V_{th}$                     | Thermoneutral voltage                                           | V                           |
| $W_{comp}$                   | Compression work                                                | kW                          |
| $x_L$                        | Part-load factor (electrolyser)                                 | –                           |
| $x_{min}$                    | Minimum load fraction                                           | –                           |
| $z$                          | Altitude                                                        | km                          |
| $\beta$                      | Tilt angle of PV panels                                         | deg                         |
| $\gamma$                     | Temperature coefficient of PV efficiency                        | °C <sup>-1</sup>            |
| $\delta$                     | Solar declination                                               | deg                         |
| $\eta_{comp}$                | Compressor efficiency                                           | 75 %                        |
| $\eta_T$                     | Thermal efficiency correction factor for PV                     | –                           |
| $\phi$                       | Latitude                                                        | deg                         |
| $\rho$                       | Ground albedo                                                   | –                           |
| $\omega$                     | Hour angle                                                      | deg                         |



## GENERAL INTRODUCTION

# General introduction

Ammonia ( $\text{NH}_3$ ) is one of the most widely produced chemicals in the world, playing an essential role in modern agriculture as the primary feedstock for nitrogen-based fertilizers. Approximately 70–80% of global ammonia production is used for fertilizers, which are crucial for maintaining food security. However, conventional ammonia synthesis via the Haber–Bosch process relies on hydrogen derived from natural gas through steam methane reforming (SMR), resulting in significant carbon dioxide emissions: about 1–2% of global  $\text{CO}_2$  emissions. In the context of climate change and the global energy transition, there is an urgent need to decarbonise ammonia production.

Green ammonia, produced from hydrogen generated by water electrolysis powered by renewable energy sources (solar, wind), offers a promising alternative. It eliminates direct fossil fuel consumption and can serve both as a sustainable fertiliser and as a carbon-free energy carrier. Algeria, with its exceptional solar irradiation (up to 3 000  $\text{kWh/m}^2/\text{year}$  in the Sahara) and a strategic geographical position close to European markets, has a strong potential to become a major player in green hydrogen and green ammonia production. Yet, the country also faces challenges such as high ambient temperatures, dust accumulation, and limited water resources, which can significantly affect the performance of photovoltaic-based systems.

## **The central research question guiding this work is:**

To what extent can a decentralised, solar-powered green ammonia production system (combining PEM electrolysis, hydrogen storage, and Haber-Bosch synthesis) achieve techno-economic viability across Algeria's diverse climatic zones, and which location offers the best balance between production performance, economic competitiveness, and environmental benefit?

## **To answer this question, we elaborate a platform where the following hypotheses are formulated:**

- **H1 :** The platform can accurately model PV generation across diverse Algerian climatic zones using Hottel clear-sky and Liu-Jordan tilted irradiance formulations.
- **H2 :** The platform can simulate PEM electrolyser operation under variable solar input, including part-load efficiency and minimum load constraints.
- **H3 :** The platform can manage hydrogen storage with threshold-based logic, ensuring continuous reactor feed while maximising PV utilisation.
- **H4 :** The platform can reliably compute the Levelised Cost of Ammonia (LCOA) based on user-defined CAPEX, OPEX, water cost, and financial parameters.
- **H5 :** The platform can compare performance across all 58 wilayas simultaneously, identifying the most favourable locations for decentralised green ammonia production.
- **H6 :** The platform provides a practical decision-support tool for pre-feasibility studies, enabling users to adjust parameters and visualise results in real time.

This thesis focuses on the study and design of a decentralised green ammonia production system powered by solar photovoltaics, intended for agricultural applications across Algeria.

The work includes :

- Modelling of the entire production chain : PV energy generation, PEM electrolysis, hydrogen storage, and Haber–Bosch synthesis.
- Development of an interactive simulation platform (Dash/Plotly) that allows users to configure system parameters, visualise real-time operation, and compare performance across all 58 wilayas.
- Techno-economic analysis to compute the Levelised Cost of Ammonia (LCOA), including CAPEX, OPEX, water supply costs and financial parameters.
- Case study comparing three representative wilayas (Djelfa, Tipaza, Adrar) to assess the influence of climate (temperature, dust) and solar resource on production and costs.
- Sensitivity analysis to assess the impact of system scale (PV peak power) on ammonia production and LCOA.

**The document is organised as follows :**

**Chapter 1** reviews the literature on ammonia production methods, the status of green hydrogen, and the Algerian context.

**Chapter 2** presents the mathematical models for PV generation, electrolysis, storage, synthesis and LCOA.

**Chapter 3** describes the architecture and features of the developed simulation platform.

**Chapter 4** applies the platform to a case study, discusses results, and concludes with recommendations.



CHAPTER 1 :  
LITTERATURE REVIEW

# CHAPTER 1 : LITERATURE REVIEW

## 1.1 Introduction [1]

Ammonia  $\text{NH}_3$  is a chemical compound composed of one nitrogen atom and three hydrogen atoms linked by covalent bonds. Under standard temperature and pressure conditions, it exists as a colorless gas with a characteristic pungent odor. Due to its high solubility in water, ammonia readily forms an alkaline solution known as aqueous ammonia.

From a physicochemical standpoint, ammonia exhibits several properties that have contributed to its widespread industrial use. It has a relatively low molar mass of 17.03 g/mol and a boiling point of  $-33.4\text{ }^\circ\text{C}$  at atmospheric pressure. These characteristics allow ammonia to be liquefied and stored under moderate pressure conditions, making its transportation and storage easier than those of gaseous hydrogen. In addition, ammonia is sufficiently stable for long-term storage while remaining reactive enough for a wide range of industrial processes.

Ammonia is an essential component of the global nitrogen cycle. Nitrogen is a vital nutrient for plant growth, yet atmospheric nitrogen  $\text{N}_2$  cannot be directly assimilated by most plants. Ammonia provides a bioavailable form of nitrogen, which explains its central role in modern agriculture. Today, the majority of ammonia produced worldwide is used either directly as a fertilizer or as a precursor for nitrogen-based fertilizers such as urea, ammonium nitrate, and ammonium sulfate. It is estimated that more than 70% of global ammonia production is dedicated to agricultural applications.

Industrial ammonia production is dominated by the Haber–Bosch process, developed in the early twentieth century and still considered one of the most significant technological achievements in the history of chemical engineering. In this process, nitrogen extracted from air reacts with hydrogen under elevated temperatures ( $400\text{--}500\text{ }^\circ\text{C}$ ) and pressures (150–300 bar) in the presence of an iron-based catalyst to produce ammonia. Although highly efficient and mature, this process requires substantial energy input and relies heavily on hydrogen obtained from fossil fuels, particularly natural gas. Consequently, conventional ammonia production is associated with considerable carbon dioxide emissions and contributes significantly to the environmental footprint of the chemical industry.

Beyond agriculture, ammonia has numerous industrial applications. It is widely used as a refrigerant (R717) due to its excellent thermodynamic properties and zero ozone depletion potential. It also serves as a key feedstock in the production of explosives, plastics, synthetic fibers, pharmaceuticals, and various chemical intermediates. In recent years, ammonia has attracted increasing attention in the energy sector because of its potential role as a carbon-free energy carrier. Owing to its hydrogen content of approximately 17.6 wt.%, ammonia can facilitate the storage and transportation of hydrogen over long distances while benefiting from an already established global infrastructure.

Despite these advantages, ammonia presents several challenges. It is toxic when inhaled at elevated concentrations and can pose risks to human health and the environment if improperly handled. Furthermore, its corrosive nature requires the use of suitable materials and dedicated safety systems throughout storage, transportation, and industrial operation.

In the context of global decarbonization efforts, the concept of green ammonia has emerged as a promising alternative to conventional ammonia production. Green ammonia is synthesized using hydrogen generated from water electrolysis powered by renewable energy sources such

as solar or wind energy. By replacing fossil-derived hydrogen with renewable hydrogen, it becomes possible to significantly reduce greenhouse gas emissions associated with ammonia production. As a result, green ammonia is increasingly viewed not only as a sustainable fertilizer feedstock but also as a potential energy vector capable of supporting the transition toward low-carbon energy systems.

## 1.2 Ammonia production methods

The industrial production of ammonia is closely linked to the method used for hydrogen generation. Since hydrogen constitutes one of the two reactants required in the Haber–Bosch synthesis process, its production route largely determines the environmental impact, energy consumption, and economic viability of ammonia manufacturing. Depending on the origin of hydrogen, ammonia can generally be classified as grey, blue, or green ammonia.

### 1.2.1 Conventional Ammonia Production via Steam Methane Reforming (Grey Ammonia) [2]

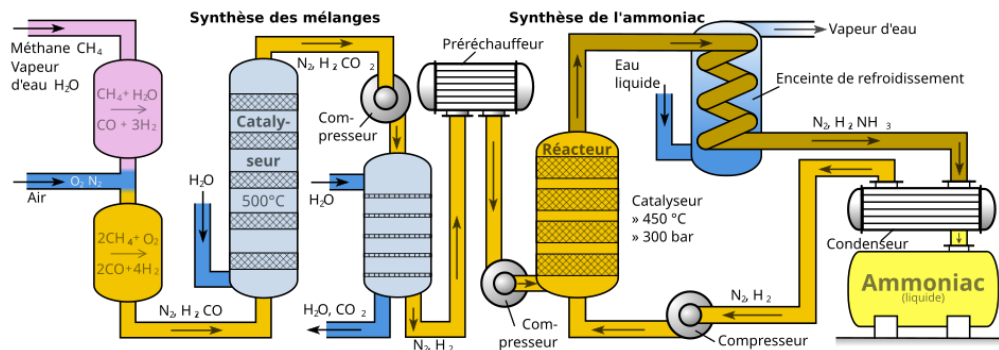


Figure 1.1: Ammonia production process

Currently, the vast majority of ammonia produced worldwide relies on hydrogen obtained from natural gas through Steam Methane Reforming (SMR). This technology is widely adopted due to its technological maturity, high efficiency, and relatively low production cost.

The process begins with the reforming of methane in the presence of steam at high temperature (typically 800–900 °C) over a nickel-based catalyst. The main reaction is expressed as:



The resulting synthesis gas, commonly referred to as syngas, contains hydrogen, carbon monoxide, carbon dioxide, and residual methane.

To increase hydrogen production, the carbon monoxide generated during reforming is converted into carbon dioxide through the Water-Gas Shift (WGS) reaction :



Subsequently, carbon dioxide and other impurities are removed using gas purification systems such as pressure swing adsorption (PSA) or chemical absorption processes. Nitrogen is then introduced, generally through air separation or secondary reforming, to obtain the stoichiometric mixture required for ammonia synthesis.

The purified hydrogen and nitrogen mixture is fed into the Haber–Bosch reactor, where ammonia is synthesized under high-pressure (150–300 bar) and high-temperature (400–500 °C) conditions in the presence of an iron-based catalyst :



The ammonia produced is subsequently condensed and separated from the unreacted gases. Because the conversion per pass remains limited by thermodynamic equilibrium, the unreacted hydrogen and nitrogen are recycled to improve the overall process efficiency.

Although this technology dominates current industrial production, it is associated with significant carbon dioxide emissions due to the use of natural gas both as a feedstock and as an energy source.

### 1.2.2 Ammonia Production with Carbon Capture and Storage (Blue Ammonia)

Blue ammonia is produced using the same fundamental process as conventional ammonia production. Hydrogen is generated through steam methane reforming and subsequently converted into ammonia via the Haber–Bosch process.

The main difference lies in the integration of Carbon Capture and Storage (CCS) technologies. During hydrogen production, a large fraction of the carbon dioxide generated by reforming and shift reactions is captured before being released into the atmosphere. The captured CO<sub>2</sub> can then be compressed, transported, and permanently stored in suitable geological formations.

### 1.2.3 Green Ammonia Production [2]

Green ammonia is produced using hydrogen generated from water electrolysis powered by renewable electricity sources such as solar or wind energy. Unlike conventional and blue ammonia pathways, this production route eliminates the direct use of fossil fuels during hydrogen generation.

Water electrolysis decomposes water molecules into hydrogen and oxygen according to the following reaction :



The hydrogen produced is subsequently combined with nitrogen extracted from the atmosphere and converted into ammonia through the Haber–Bosch process.

The principal advantage of green ammonia lies in its very low carbon footprint when renewable electricity is used throughout the process. In addition to its role as a sustainable fertilizer feedstock, green ammonia is increasingly considered a promising energy carrier capable of facilitating hydrogen storage, transportation, and international trade.

Environmental and financial assessments confirm that ongoing technological improvements and declining renewable energy costs are expected to enhance the competitiveness of green ammonia over the coming decades.

## 1.3 Current Status of Ammonia

### 1.3.1 Global Overview [1]

Ammonia is one of the most important chemicals produced worldwide due to its essential role in agriculture and industry. Global ammonia production is currently estimated at approximately

180 million tonnes per year, making it one of the largest-volume chemical products manufactured worldwide. Production is geographically concentrated in regions benefiting from abundant energy resources and large agricultural markets. China is the leading producer, followed by India, the United States, Russia, and several countries in the Middle East.

The importance of ammonia is primarily linked to its use in the fertilizer industry. Approximately 70–80% of global ammonia production is converted into nitrogen-based fertilizers such as urea, ammonium nitrate, and ammonium sulfate. These fertilizers play a crucial role in maintaining agricultural productivity and ensuring food security for a growing global population. The remaining production is utilized in various industrial sectors, including refrigeration, explosives manufacturing, pharmaceuticals, plastics, and synthetic fibers.

Beyond its traditional applications, ammonia has recently attracted increasing interest in the energy sector. Unlike fossil fuels, ammonia contains no carbon atoms and therefore does not generate carbon dioxide emissions during combustion. Moreover, its relatively high volumetric energy density and existing transportation infrastructure make it a promising candidate for energy storage and long-distance hydrogen transport.

Despite its numerous advantages, conventional ammonia production remains associated with substantial environmental impacts. The Haber–Bosch process requires large quantities of hydrogen, which is currently produced mainly from natural gas and coal. Consequently, ammonia production is highly energy-intensive and contributes significantly to global greenhouse gas emissions. Recent studies estimate that the ammonia industry is responsible for approximately 1–2% of global carbon dioxide emissions, highlighting the importance of developing cleaner production pathways.

These environmental concerns have accelerated research and investment efforts toward low-carbon ammonia production technologies, particularly blue ammonia and green ammonia. Such alternatives are increasingly viewed as essential for reducing the environmental footprint of both the fertilizer sector and emerging ammonia-based energy applications.

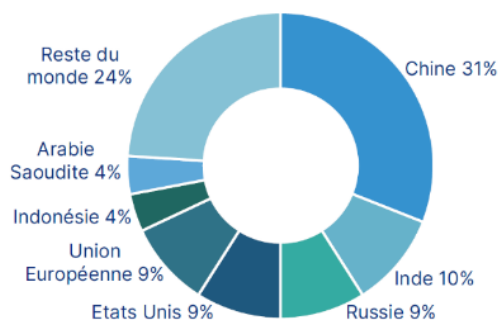


Figure 1.2 : Global ammonia production in the world

### 1.3.2 The Situation in Algeria

In Algeria, ammonia occupies a strategic position within both the agricultural and industrial sectors. The country's significant natural gas reserves have enabled the development of a well-established ammonia and fertilizer industry based on conventional Haber–Bosch technology. For several decades, ammonia production has contributed to the valorization of national hydrocarbon resources while supporting domestic agricultural activities.

The Algerian ammonia industry is mainly concentrated around large petrochemical and fertilizer complexes located in Annaba and Arzew. These industrial sites produce ammonia as an intermediate product for the manufacturing of nitrogen fertilizers, particularly urea and

ammonium nitrate. The fertilizer sector plays an important role in supporting agricultural productivity by providing essential nutrients for crop development, especially in cereal-growing regions.

In addition to satisfying domestic demand, Algeria exports substantial quantities of ammonia and fertilizer products to international markets. These exports contribute to generating foreign currency revenues and strengthening the country's position within the regional petrochemical industry. The proximity of European markets also provides logistical advantages for ammonia and fertilizer exports.

However, as in many producing countries, conventional ammonia production in Algeria remains highly dependent on natural gas. While this dependency offers economic benefits due to abundant domestic resources, it also results in significant carbon dioxide emissions. Consequently, future environmental regulations and international decarbonization policies may increasingly affect the competitiveness of fossil-based ammonia production.

For this reason, interest in green ammonia has grown considerably in recent years. Algeria possesses exceptional solar resources, particularly in the Saharan regions, where annual solar irradiation levels rank among the highest in the world. These favorable conditions create significant opportunities for coupling photovoltaic electricity generation with water electrolysis to produce renewable hydrogen and, subsequently, green ammonia.

Several national initiatives and international cooperation programs are currently evaluating the technical and economic feasibility of green hydrogen and green ammonia projects in Algeria. Such projects could simultaneously support industrial decarbonization, strengthen energy diversification, and create new export opportunities targeting future low-carbon markets.

Furthermore, green ammonia could play a particularly important role in remote agricultural regions where decentralized production systems may reduce transportation costs and improve fertilizer accessibility. This perspective is especially relevant in the context of decentralized renewable energy systems, which constitute the central focus of this research work.

## 1.4 The Status of Green Hydrogen

### 1.4.1 Global Overview [3]

Hydrogen has become a strategic component of the global energy transition due to its potential to decarbonize sectors that are difficult to electrify, including heavy industry, long-distance transport, and chemical production. In recent years, governments and industries worldwide have increasingly recognized hydrogen as a key energy carrier capable of supporting climate neutrality objectives, enhancing energy security, and strengthening industrial competitiveness.

According to the International Energy Agency (IEA), global hydrogen demand reached nearly 100 million tonnes in 2024, representing an increase of approximately 2% compared with the previous year. This growth was primarily driven by conventional applications such as oil refining, ammonia production, methanol synthesis, and other industrial processes.

The current hydrogen market remains largely dependent on fossil-fuel-based production pathways. Natural gas and coal continue to dominate global hydrogen production, while low-emission hydrogen contributes less than 1% of total supply. Nevertheless, the deployment of low-emission hydrogen technologies has accelerated significantly over the last five years,

reflecting growing international commitments toward decarbonization and sustainable energy systems.

The low-emission hydrogen sector has experienced substantial progress since the beginning of the decade. While only a limited number of demonstration projects existed in 2020, more than 200 projects worldwide have now reached final investment decisions, indicating increasing confidence among investors and policymakers. Although several projects have been delayed or cancelled due to high production costs, regulatory uncertainty, and infrastructure constraints, the long-term outlook remains positive. The IEA estimates that low-emission hydrogen production could increase from approximately 0.8 Mtpa today to more than 4.2 Mtpa by 2030 based solely on projects that are already operational, under construction, or have secured final investment decisions. This expansion is supported by continuous technological progress, declining renewable energy costs, and increasing policy support mechanisms designed to stimulate both hydrogen production and consumption.

China has emerged as the global leader in hydrogen deployment, particularly in renewable hydrogen production and electrolyser manufacturing. By 2024, China accounted for approximately 60% of global electrolyser manufacturing capacity and more than half of the world's installed electrolyser capacity. The country's rapid expansion has been driven by strong governmental support, extensive renewable energy resources, large-scale industrial demand, and highly competitive manufacturing capabilities. In addition, China has achieved some of the lowest renewable hydrogen production costs worldwide, strengthening its position within the global hydrogen economy.

Alongside China, regions such as the European Union, the United States, Japan, South Korea, and India have adopted ambitious hydrogen strategies aimed at accelerating production, developing infrastructure, and creating market demand through dedicated policy frameworks and financial incentives.

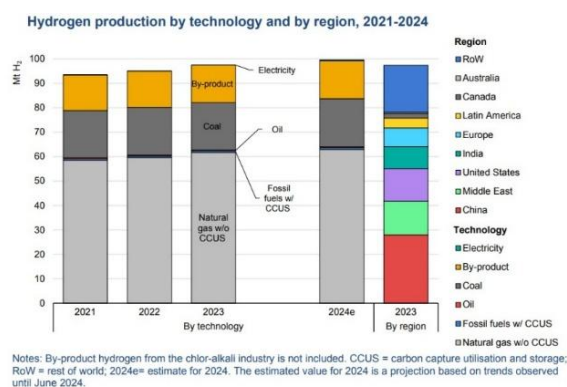


Figure 1.3 : Hydrogen in the world

## 1.4.2 In Algeria

Algeria, historically dependent on hydrocarbons, is currently facing major challenges linked to the global energy transition, the decarbonization of energy systems, and the diversification of its national economy. Within this context, green hydrogen emerges as a strategic energy vector capable of leveraging the country's vast renewable resources while preparing for the post-natural gas era. National energy policies are increasingly prioritizing renewable energy and hydrogen, notably through the National Renewable Energy Development Program and the initial frameworks of a dedicated national hydrogen strategy [4].

Algeria's primary asset for green hydrogen development lies in its exceptional solar potential. The Algerian territory benefits from one of the highest solar irradiation levels in the world, with

annual values exceeding **2 000 kWh/m<sup>2</sup>/year** across a large part of the country and reaching up to **3 000 kWh/m<sup>2</sup>/year** in Saharan regions.

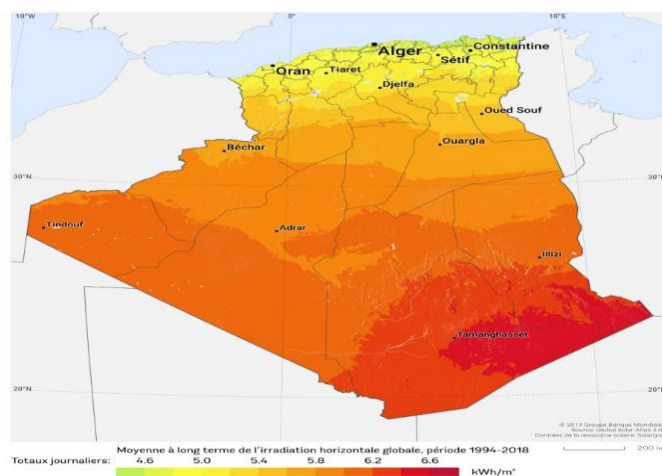


Figure 1.4 : Solar radiation in Algeria

This abundant solar resource creates opportunities for large-scale photovoltaic (PV) power generation, which can be directly coupled with water electrolyzers for green hydrogen production. Southern regions, such as Adrar, Tamanrasset, Illizi, and In Salah, exhibit particularly high yields, confirming their natural suitability for high-capacity green hydrogen production facilities [5].

The table below presents the estimated solar hydrogen production rates in Algeria, established by the Centre de Développement des Énergies Renouvelables (CDER) over the period 1992–1996. These historical data illustrate the potential for hydrogen production from renewable sources in Algeria, identified as early as the 1990s. Although these estimates are dated, they provide a useful reference for understanding the evolution of technologies and the persistence of Algeria's exceptional solar potential, particularly in the Saharan regions.

Table 1.1 : Estimated Probable Hydrogen Production Rate by CDER (1992–1996)

| Site             | Insolation<br>KWh/m <sup>2</sup> | Production H <sub>2</sub><br>(l/m <sup>2</sup> /j) | Site            | Insolation<br>KWh/m <sup>2</sup> | Production<br>H <sub>2</sub> (l/m <sup>2</sup> /j) |
|------------------|----------------------------------|----------------------------------------------------|-----------------|----------------------------------|----------------------------------------------------|
| 1 Beni-Saf       | 4,85                             | 96,77                                              | 28 Constantine  | 4,41                             | 87,99                                              |
| 2 Oran           | 4,59                             | 91,52                                              | 29 Batna        | 4,55                             | 90,71                                              |
| 3 Arzew          | 4,38                             | 87,25                                              | 30 Souk Ahras   | 4,38                             | 87,35                                              |
| 4 Mostaganem     | 4,55                             | 90,75                                              | 31 Tébessa      | 4,78                             | 95,35                                              |
| 5 Maghnia        | 4,91                             | 97,96                                              | 32 Saïda        | 4,92                             | 98,02                                              |
| 6 Tiemcen        | 4,88                             | 97,28                                              | 33 El Kheiter   | 5,02                             | 100,03                                             |
| 7 Mascara        | 4,53                             | 90,36                                              | 34 El Bayadh    | 5,00                             | 99,74                                              |
| 8 S.B. Abbès     | 4,92                             | 98,05                                              | 35 Mecheria     | 4,99                             | 99,39                                              |
| 9 Chlef          | 4,58                             | 91,23                                              | 36 Ain Sefra    | 5,32                             | 106,12                                             |
| 10 Ténès         | 4,43                             | 88,28                                              | 37 Naâma        | 5,04                             | 100,49                                             |
| 11 Miliana       | 4,49                             | 89,44                                              | 38 Béchar       | 5,57                             | 111,08                                             |
| 12 Média         | 4,41                             | 87,98                                              | 39 Biskra       | 5,08                             | 101,21                                             |
| 13 Alger         | 4,40                             | 87,76                                              | 40 Chardaia     | 5,47                             | 109,14                                             |
| 14 Tizi-Ouzou    | 4,37                             | 87,19                                              | 41 Thouggourt   | 5,23                             | 104,20                                             |
| 15 Bouira        | 4,49                             | 89,60                                              | 42 El oued      | 5,17                             | 102,97                                             |
| 16 Béjaia        | 4,30                             | 85,79                                              | 43 Ouargla      | 5,39                             | 107,39                                             |
| 17 Jijel         | 4,34                             | 86,55                                              | 44 El Goléa     | 5,71                             | 113,89                                             |
| 18 Skikda        | 4,33                             | 86,35                                              | 45 TSmSmoun     | 5,79                             | 115,4                                              |
| 19 Annaba        | 4,36                             | 87,00                                              | 46 Béni Abbès   | 5,79                             | 115,51                                             |
| 20 Guelma        | 4,36                             | 86,96                                              | 47 Adrar        | 5,93                             | 118,14                                             |
| 21 Tiaret        | 4,82                             | 96,00                                              | 48 In Salah     | 5,97                             | 118,96                                             |
| 22 Djelfa        | 4,89                             | 97,50                                              | 49 In Amenas    | 5,91                             | 117,78                                             |
| 23 K.Chellala    | 4,89                             | 97,48                                              | 50 Djanet       | 6,28                             | 125,10                                             |
| 24 M'sila        | 4,66                             | 92,88                                              | 51 Tamanrasset  | 6,15                             | 122,53                                             |
| 25 Boussaâda     | 4,84                             | 96,53                                              | 52 Asserkrem    | 6,22                             | 123,95                                             |
| 26 B.B. Arreridj | 4,54                             | 90,52                                              | 53 B.B. Mokhtar | 6,13                             | 122,17                                             |
| 27 Sétif         | 4,52                             | 90,18                                              | 54 In Guezem    | 6,22                             | 123,98                                             |

The geographical distribution of hydrogen potential in Algeria reveals a distinct differentiation between three main zones:

- **The North:** Although highly industrialized and densely populated, this region features more moderate solar potential. This limits its viability for massive green hydrogen production but makes it highly relevant for local or decentralized applications.

- **The High Plateaus:** This zone offers an advantageous compromise between high solar irradiance, land availability, and relative proximity to existing infrastructure, making it highly favorable for pilot and semi-industrial projects.
- **The Sahara:** This region concentrates the highest potential, offering optimal climatic conditions and vast available land, establishing it as a strategic zone for large-scale, export-oriented projects.

Algeria also possesses a significant structural advantage due to its existing energy infrastructure, particularly its natural gas transmission network connecting the country to European markets. In the medium to long term, these pipelines could be partially retrofitted to transport hydrogen–natural gas blends or even pure hydrogen.

This would reinforce Algeria's role as a major future player in the Euro-Mediterranean green hydrogen market [3]. This strategic geographical positioning, combined with recognized industrial expertise in the energy sector, grants the country a notable competitive edge.

## 1.5 Installed Photovoltaic (PV) Capacity in Algeria

The development of solar photovoltaic (PV) energy in Algeria remains modest compared to its stated ambitions. Nevertheless, significant progress has been achieved in recent years, as shown in the figure below :



Figure 1.5 : Projected National Megawatt Capacity and Current Progress

## 1.6 Water Resources in Algeria

**Surface and Groundwater Availability :** Algeria's total surface water potential is relatively constrained, not exceeding 12.7 billion m<sup>3</sup>/year. However, total water mobilization can be increased up to 18.3 billion m<sup>3</sup>/year by tapping into northern and southern groundwater aquifers, supplemented by seawater desalination. [6]

**Wastewater Assets :** In addition to conventional sources, Algeria generates nearly 2 billion m<sup>3</sup> of wastewater. The nominal volume of effectively treated wastewater stands at 700 hm<sup>3</sup>/year. [7]

Within the framework of this thesis, the utilization of treated wastewater will be prioritized over other non-conventional water sources. This strategic choice is guided by two main factors :

**Infrastructure Availability :** There are 134 Wastewater Treatment Plants (WWTPs) operational across the national territory, compared to only 23 Seawater Desalination Plants.

**Economic and Energetic Viability :** The seawater desalination infrastructure currently deployed in Algeria relies heavily on reverse osmosis (RO). While effective, this technology is highly capital-intensive and demands significant energy consumption [8], making treated wastewater a more sustainable and cost-effective alternative for localized industrial applications like green hydrogen and ammonia production.

## 1.7 Decentralized Green Ammonia Production from Photovoltaics



Figure 1.6 : Green ammonia value chain

### 1.7.1 Electrolyzer Technologies [9]

An electrolyser is a composition of three elements :

- 1. The Anode :** The site of the oxidation reaction where dioxygen (O<sub>2</sub>) gas is released.
- 2. The Cathode :** The site of the reduction reaction where dihydrogen (H<sub>2</sub>) gas is formed.
- 3. The Electrolyte :** The conductive medium that ensures ion transport between the two electrodes under the influence of an electric voltage.

The performance of these systems is evaluated based on three major criteria: energy efficiency, operating temperature, and the purity level of the produced gas.

The table below compares the three main electrolysis technologies: alkaline (AEL), proton exchange membrane (PEM), and solid oxide (SOEC). It summarises their charge carriers, electrolytes, electrode materials, operating temperatures, and typical efficiencies.

Table 1.2 : Characteristics of electrolysis technologies

| Characteristic                     | Alkaline Electrolyzer (AEL)                | PEM Electrolyzer (PEM)          | Solid Oxide Electrolyzer (SOEC) |
|------------------------------------|--------------------------------------------|---------------------------------|---------------------------------|
| Charge carrier                     | $\text{OH}^-$                              | $\text{H}^+$                    | $\text{O}^{2-}$                 |
| Electrolyte                        | Liquid solution (Potassium hydroxide, KOH) | Solid polymer membrane (Nafion) | Solid ceramic                   |
| Anode Material                     | Nickel / Nickel-plated steel               | Precious metal: Iridium         | Ceramic (Perovskites)           |
| Cathode Material                   | Nickel / Nickel-plated steel               | Precious metal: Platinum        | Cermet (Nickel)                 |
| Temperature ( $^{\circ}\text{C}$ ) | 70 – 90                                    | 50 – 80                         | 700 – 850                       |
| Illustration                       |                                            |                                 |                                 |

## Electrode Chemical Equations :

The table below presents the electrochemical reactions at the electrodes for each electrolysis technology.

Table 1.3 : Electrode Chemical Equations

| Type | Cathode                                                                         | Anode                                                                            |
|------|---------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| AEL  | $2\text{H}_2\text{O} + 2\bar{e} \rightarrow \text{H}_2 + 2\text{OH}^-$          | $2\text{OH}^- \rightarrow \frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2\bar{e}$ |
| PEM  | $\text{H}_2\text{O} \rightarrow \frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2\bar{e}$ | $2\text{H}^+ + 2\bar{e} \rightarrow \text{H}_2$                                  |
| SOEC | $\text{H}_2\text{O} + 2\bar{e} \rightarrow \text{H}_2 + \text{O}_2^-$           | $\text{O}_2^- \rightarrow \frac{1}{2}\text{O}_2 + 2\bar{e}$                      |

| Electrolysis Types            | Advantages and Technologies                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Disadvantages and Technologies                                                                                                                                                                                                                                                                                                                                                                                                                            |
|-------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Alkaline Electrolysis         | <ul style="list-style-type: none"> <li>• Oldest and well-established technology</li> <li>• Cheapest and effective cost</li> <li>• Noble-type catalyst</li> <li>• Long-term durability</li> <li>• MW range stacks</li> <li>• 70% efficiency</li> <li>• Nickel-coated stainless steel electrodes</li> <li>• Nickel mesh for diffusion layer</li> <li>• Nickel-coated stainless steel bipolar plate</li> <li>• Polysulfone for frame and sealing</li> </ul>                                                  | <ul style="list-style-type: none"> <li>• Low current density</li> <li>• Low degree of purity</li> <li>• Corrosive liquid electrolyte</li> <li>• Low dynamic operation</li> <li>• Low load range for partial load</li> <li>• Low operating pressure</li> <li>• Crossover of gas</li> </ul>                                                                                                                                                                 |
| PEM Electrolysis              | <ul style="list-style-type: none"> <li>• High current density</li> <li>• High voltage efficiency</li> <li>• Good partial load range</li> <li>• Compact system design</li> <li>• The high degree of gas purity</li> <li>• High dynamic operation</li> <li>• Rapid system response</li> <li>• Iridium oxide electrode oxygen side</li> <li>• Platinum nanoparticles electrode hydrogen side</li> <li>• Sintered porous titanium for diffusion layer</li> <li>• Polysulfone for frame and sealing</li> </ul> | <ul style="list-style-type: none"> <li>• New and partially established technology</li> <li>• High cost of components</li> <li>• Acidic environment corrosion</li> <li>• Comparatively low durability</li> <li>• Below MW range stack</li> <li>• Limited and costly membrane</li> <li>• Commercialization is in the near term</li> <li>• Higher discharge pressure</li> <li>• Mature and small-scale technology</li> <li>• Nobel metal catalyst</li> </ul> |
| High-Temperature Electrolysis | <ul style="list-style-type: none"> <li>• 100% efficiency</li> <li>• Thermal neutral efficiency &gt; 100%</li> <li>• Non-noble catalyst</li> <li>• High-pressure operation</li> <li>• Perovskite-type electrode</li> <li>• Cobalt-coated stainless steel bipolar plate</li> <li>• Nickel foam for diffusion-layer anode</li> </ul>                                                                                                                                                                         | <ul style="list-style-type: none"> <li>• Laboratory-phase technology</li> <li>• Low durability due to high heat, ceramics</li> <li>• Bulk system design</li> <li>• No diffusion layer cathode</li> <li>• No bipolar plate anode</li> <li>• Ceramic glass for frame and sealing</li> </ul>                                                                                                                                                                 |

Figure 1.7 : Advantages and disadvantages of Electrolysis types

Considering the fluctuating nature of solar power generation, PEM electrolyser is chosen in this work because of its superior compatibility with renewable energy systems, characterized by fast start-up times, high current density operation, and excellent performance under fluctuating power conditions, which are essential for maximizing hydrogen production from variable solar energy resources.

## 1.7.2 Hydrogen Storage [10]

Dihydrogen, due to its very low volumetric density under ambient conditions, requires specific conditioning solutions to enable safe and efficient storage and transport. Three main storage approaches can be distinguished : physical storage in gaseous form, physical storage in liquid form, and solid-state storage, which relies on physical or chemical interactions with host materials.

### 1.7.2.1 Gaseous state

At ambient temperature, because the volumetric density of dihydrogen is extremely low, its storage requires high-pressure compression. Industrial systems typically utilize tanks operating at pressures between 150 and 700 bar, depending on the application.

Storage tanks must satisfy strict normative and regulatory requirements to guarantee a high level of safety, notably resistance to high internal pressures, mechanical fatigue, and hydrogen embrittlement. Hydrogen gas cylinders are classified into four types based on their design and the materials used :

**Type I :** All-metal tank (steel or aluminum). It is economically advantageous but very heavy, and limited to pressures around 200 bar.

**Type II :** Metal tank hoop-wrapped with a composite material around the cylindrical part.

**Type III :** Tank featuring a metallic liner fully wrapped with composite materials (carbon or glass fibers). It offers a good compromise between mass and strength, making it suitable for mobile applications.

**Type IV :** Tank consisting of a polymer liner with metallic bosses, fully wrapped in a composite matrix. This is the lightest solution, although challenges remain regarding sealing and hydrogen permeation.

### 1.7.2.2 Liquid State

Storing hydrogen in liquid form allows for a significantly higher volumetric density than compressed gas. Dihydrogen transitions to a liquid state at  $-253\text{ }^{\circ}\text{C}$  (20.3 K) under atmospheric pressure. Storage therefore requires cryogenic tanks with high-performance thermal insulation systems. Nevertheless, boil-off losses remain unavoidable due to thermal leakage, ortho-to-para hydrogen conversion, sloshing effects, and transfer operations.

### 1.7.2.3 Solid State

Solid-state storage relies on adsorption, absorption, or chemical reactions between hydrogen and a host material. This approach enables storage at moderate pressure and offers enhanced operational safety. However, several challenges remain, including high material mass, slow kinetics, thermal management requirements, material degradation, and elevated costs.

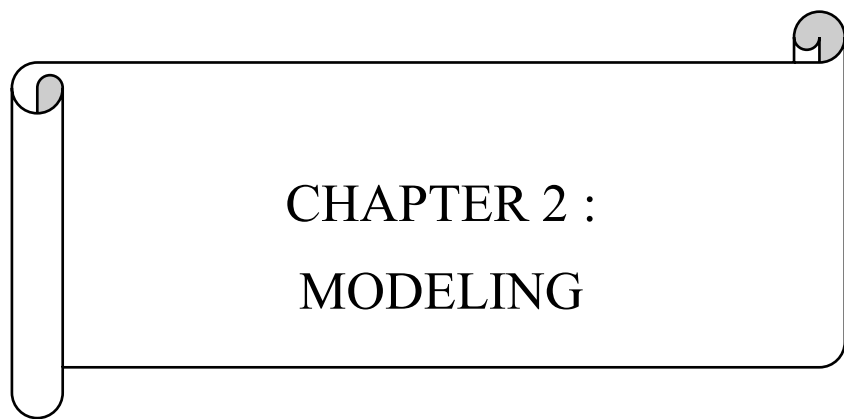
This table lists the main families of materials used for solid-state hydrogen storage

Table 1.4 : Materials for Solid state storage of hydrogen

| Materials                                                       | Examples                                                                                                                                                                                                       |
|-----------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Carbon and High Specific Surface Area Materials (Physisorption) | <ul style="list-style-type: none"> <li>* Activated carbon</li> <li>* Graphite nanotubes and nanofibers</li> <li>* Zeolites</li> <li>* Metal-organic frameworks (MOFs)</li> <li>* Clathrate hydrates</li> </ul> |
| Rechargeable Hydrides (Chemical Storage)                        | <ul style="list-style-type: none"> <li>* Intermetallic compounds and alloys</li> <li>* Complex compounds</li> <li>* Nanocrystals</li> <li>* Magnesium hydrides (<math>Mg_2FeH_6</math>)</li> </ul>             |
| Chemical Hydrides (Hydrolysis)                                  | <ul style="list-style-type: none"> <li>* Encapsulated sodium hydride (NaH)</li> <li>* Lithium, calcium, and magnesium hydrides</li> </ul>                                                                      |
| Chemical Hydrides (Thermal Decomposition)                       | <ul style="list-style-type: none"> <li>* Complex hydrides (<math>LiAlH_4</math> ; <math>NaAlH_4</math>)</li> </ul>                                                                                             |

| Type of storage                 | Strength                                                                                                                                   | Weakness                                                                                                                                                                                                                                                                                  | Opportunities                                                                                                                                                                                                                                    | Threats                                                                                                                                                                                     |
|---------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Compressed hydrogen gas storage | Well-understood up to pressures of 200 bar; generally available; can be low-cost                                                           | Only relatively small amounts of $H_2$ are stored at 200 bar; fuel and storage energy densities at high pressure (700 bar) are comparable to liquid hydrogen                                                                                                                              | Advancement in the fabrication of tanks can mitigate the risk involved due to tank explosion.                                                                                                                                                    | Safety issues due to high-pressure storage.<br>Due to the limited storage capacity, it would require frequent refueling and will have a low range.                                          |
| Liquid hydrogen storage         | Well-understood technology; good storage density possible                                                                                  | Very low temperatures require super insulation; cost can be high; some hydrogen is lost through evaporation; energy intensity of liquid hydrogen production; energy stored still not comparable to liquid fossil fuels                                                                    | With the improvement in cryogenic technologies and integration with other cooling systems, could enhance the applicability of this technology                                                                                                    | High energy consumption owing to the liquefaction of gas.<br>High initial investment for construction of specialized infrastructure.                                                        |
| Metal Hydride Storage           | Solid-state storage; can be made into different shapes. Safer method due to the stability of the chemical reaction. High storage capacity. | Heavy; Can degrade with time; currently expensive; The operating temperature is high, necessitating the need for cooling system. Poor thermal conductivity of powder beds can restrict the kinetics; Slow kinetics; Lanthanum penta-nickel is an alloy that operates at room temperature. | The storage of hydrogen in metal hydrides for stationary applications, although it has not yet seen any commercial application or large-scale demonstration because it is still in the research stage, may play an important role in the future. | Expensive material cost and paucity of suitable hydrides. Low durability and cycling stability.                                                                                             |
| Chemical Hydride                | Capable of storing high-density hydrogen gas. Potential for storing gas at room temperature and low pressure                               | It follows a slow kinetic for hydrogen storage and regeneration                                                                                                                                                                                                                           | Developing efficient catalyst and reaction condition<br>Integration with renewable energy sources for long-term hydrogen production                                                                                                              | Scalability issue for large-scale commercial applications.<br>Potential depletion of hydride material, along with limited cycle life                                                        |
| Carbon based material storage   | Capable of storing large amounts of hydrogen gas. The potential of operating at room temperature.                                          | Not fully understood or developed; early promise remains unfulfilled. Complex manufacturing process, along with difficulty in achieving desorption and adsorption process                                                                                                                 | The advancement of carbon-based nano structure and capability of working in conjunction with other energy systems.                                                                                                                               | Scalability for large-scale commercial application<br>Carbon-nanotube production may pose environmental concerns.                                                                           |
| Hydrate-based hydrogen storage  | Easy and energy-efficient hydrogen release, Safe, Potentially no expensive and toxic materials                                             | Currently slow kinetics of gas hydrate conversion<br>Currently low hydrogen density in solid hydrates                                                                                                                                                                                     | Well-fitted in the global roadmap for clean energy<br>Supports from Government and Industry<br>Align with the emerging hydrogen energy                                                                                                           | Competition with other technologies<br>Unclear long-term stability of hydrogen hydrates<br>Unclear about techno-economic feasibility.<br>No pre-knowledge regarding industrial applications |

Figure 1.8 : SWOT of hydrogen storage



## CHAPTER 2 : MODELING

# CHAPTER 2 : MODELING

## 2.1 Model Assumptions

- **Clear-Sky Conditions** : A clear sky is assumed ; the attenuation effects of cloud cover are not modeled.
- **Fixed System Sizing** : The PV peak power and the electrolyzer capacity are kept constant across all simulated wilayas.
- **Constant Ambient Temperature** : The ambient temperature is assumed to be constant throughout the simulated day and is set equal to the annual average temperature of the respective wilaya.
- **Albedo Coefficients** : The ground albedo coefficient is fixed at **0.2** for coastal cities and the High Plateaus, and at **0.4** for the southern Saharan regions.
- **Fouling Factor** : The PV soiling/fouling factor is set to **0.8** for coastal cities and the High Plateaus, and to **0.6** for the southern Saharan regions (accounting for higher dust and sand accumulation).
- **Process Boundaries** : This study focuses on system-level energy performance; a detailed thermodynamic analysis of the chemical and electrochemical processes falls outside the scope of this model.
- **Electrolyser** : The electrolyzer is assumed to operate within the intermediate current-density range where ohmic losses dominate the polarization curve. In this region, the cell voltage varies approximately linearly with the current, which justifies the use of a linear electrolyzer model. The low-current activation region and the high-current mass-transport region are neglected in the present study.

## 2.2 Solar Resource and Photovoltaic Generation Modeling

### 2.2.1 Input Data Configuration per Wilaya

The specific parameters initialized for each wilaya include :

- **Geographical Coordinates** : The local latitude and longitude used to solve the astronomical geometry equations and determine the solar path throughout the year.
- **Altitude (z, in km)** : The height above sea level, which directly affects atmospheric clear-sky attenuation parameters in the Hottel transmittance model.
- **Optimal Tilt Angle ( $\beta$ )** : The specific slope inclination determined for each province to maximize the total annual incident global tilted irradiance ( $G_\beta$ ).
- **Ambient Temperature ( $T_{amb}$ )** : Regional hourly or monthly temperature profiles used to calculate the dynamic thermal behavior of the photovoltaic cells ( $T_{amb}$ ).

- **Ground Albedo ( $\rho$ )** : The local soil reflection coefficient, which varies depending on regional ground characteristics (e.g., urban surfaces, agricultural soil, or desert sand).
- **Soiling Factor ( $f_{\text{dust}}$ )** : A regional atmospheric and environmental degradation coefficient that accounts for efficiency losses caused by dust accumulation and sandstorms, particularly in the Southern Highlands and Saharan regions.

### 2.2.2 Clear Sky Model

The Hottel model allows for the estimation of clear-sky atmospheric transmittance as a function of site altitude and solar altitude angle.

The atmospheric transmission coefficients are calculated as follows:

$$A_0 = 0,4237 - 0,00821(6,0 - z)^2 \quad (2.1)$$

$$A_1 = 0,5055 + 0,00595 (6,5 - z)^2 \quad (2.2)$$

$$K = 0,2711 + 0,01858 (2,5 - z)^2 \quad (2.3)$$

Where  $z$  is the altitude in kilometers.

The atmospheric transmittance for direct (beam) radiation is given by:

$$T_b = A_0 + A_1 \cdot \exp\left(-\frac{K}{\sin(h_s)}\right) \quad (2.4)$$

And the atmospheric transmittance for diffuse radiation is given by :

$$T_d = 0.271 - 0.294 \cdot T_b \quad (2.5)$$

Where  $h_s$  is the solar altitude angle calculated from the solar declination  $\delta$ , the latitude  $\varphi$  and the hour angle  $\omega$  :

$$\sin(h_s) = \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\cos(\omega) \quad (2.6)$$

The solar declination is given by Cooper's formula:

$$\delta = 23,45 \cdot \sin\left(\frac{360 \cdot (N_j + 284)}{365}\right) \quad (2.7)$$

Where  $N_j$  is the day number of the year.

$$\omega = 15 \cdot (t_h - 12) \quad (2.8)$$

Where  $t_h$  is the Apparent Solar Time

$$t_h = \text{Temps standard} + 4 (L_{loc} - 15) + ET \quad (2.9)$$

Where  $L_{Loc}$  is the Longitude and ET is the Equation of Time correction factor given by :

$$ET = 9,87 \sin(2b) - 7.53 \cos(b) - 1.5 \sin(b) \quad (2.10)$$

With :

$$b = \frac{360}{365} (N_j - 81) \quad (2.11)$$

The extraterrestrial irradiance is corrected for the variation in the Earth-Sun distance :

$$G_e = G_0 \cdot (1 + 0,033 \cdot \cos\left(\frac{360 \cdot N_j}{365}\right)) \quad (2.12)$$

with  $G_0 = 1367 \text{ W/m}^2$  (solar constant).

The irradiance components on a horizontal plane are then:

Direct horizontal irradiance :

$$B_{0h} = G_e \cdot T_b \cdot \sin(h_s) \quad (2.13)$$

Diffuse horizontal irradiance :

$$D_{0h} = G_e \cdot T_d \cdot \sin(h_s) \quad (2.14)$$

Global horizontal irradiance :

$$G_{0h} = B_{0h} + D_{0h} \quad (2.15)$$

### 2.2.3 Irradiance on a Tilted Surface

The geometric tilt factor for direct radiation is :

$$R_b = \frac{\sin(\varphi - \beta)\sin(\delta) + \cos(\varphi - \beta)\cos(\delta)\cos(\omega)}{\sin(h_s)} \quad (2.16)$$

The total global irradiance on the tilted surface is then :

$$G_\beta = G_{0h} \cdot \left[ R_b \cdot \frac{B_{0h}}{G_{0h}} + \frac{D_{0h}}{G_{0h}} \cdot \frac{1 + \cos\beta}{2} + \rho \cdot \frac{1 - \cos\beta}{2} \right] \quad (2.17)$$

### 2.2.4 PV Cell Thermal Model

The temperature of the PV cell directly impacts its efficiency. It is estimated using the Nominal Operating Cell Temperature (NOCT) model :

$$T_{cell} = T_{amb} + \frac{NOCT - 20}{800} \cdot G_{\beta} \quad (2.18)$$

$$NOCT = 45^{\circ}C$$

The temperature coefficient  $\gamma$  reflects the efficiency loss per degree Celsius above the Standard Test Conditions (STC) reference temperature ( $25^{\circ}C$ ) :

$$\eta_T = 1 - \gamma \cdot (T_{cell} - T_{STC}) \quad (2.19)$$

Where :

$$\gamma = 0.004^{\circ}C^{-1}$$

### 2.2.5 Output Power P(t)

The electrical output power of the PV array is calculated as :

$$P_{PV}(t) = P_{peak} \times \left[ \frac{G_{\beta}(t)}{1000} \right] \times \eta_T \times f_{dust} \quad (2.20)$$

The sunrise and sunset hours are calculated analytically.

The sun rises and sets when it touches the horizon ( $h_s = 0$ ), meaning when the solar altitude is zero ( $h_s = 0$ ).

At sunrise and sunset,  $h_s = 0$  :

$$\sin \varphi \cdot \sin \delta + \cos \varphi \cdot \cos \delta \cdot \cos \omega = 0 \quad (2.21)$$

$$\cos \omega = \frac{-\sin \varphi \cdot \sin \delta}{\cos \varphi \cdot \cos \delta} = -\tan \varphi \cdot \tan \delta \quad (2.22)$$

$$\omega = \pm \arccos(-\tan \varphi \cdot \tan \delta) \quad (2.23)$$

- $\omega > 0 \rightarrow$  afternoon  $\rightarrow$  **sunset**
- $\omega < 0 \rightarrow$  morning  $\rightarrow$  **sunrise**

$$h_{sunrise} = 12 - \frac{\arccos(-\tan \varphi \cdot \tan \delta)}{15} \quad (2.24)$$

$$h_{sunset} = 12 + \frac{\arccos(-\tan \varphi \cdot \tan \delta)}{15} \quad (2.25)$$

## 2.3 Modeling of PEM Electrolyser

The theoretical minimum voltage required to split water is the thermoneutral voltage [11] :

$$V_{th} = 1.48 \text{ V}$$

In practice, the cell voltage exceeds  $V_{th}$  due to ohmic losses and activation overpotentials. It is modeled linearly as a function of the part-load factor  $x_L$ : [12]

$$V_{cell(x_L)} = V_{th} + V_{ohmic} \cdot x_L \quad (2.26)$$

Where :

$$V_{ohmic} = V_{nom} - V_{th} \quad (2.27)$$

$V_{nom}$  is the nominal voltage of the cell :

$$V_{nom} = \frac{E_{sp} \times 1000 \times M_{H_2} \times 3600}{2F} \quad (2.28)$$

Part-load factor  $x_L$  :

$$x_L = \frac{P_{elec}(t)}{P_{EL}} \quad (2.29)$$

- The effective specific energy consumption at part-load is :

$$E_{sp,eff(x_L)} = E_{sp} \cdot \frac{V_{cell(x_L)}}{V_{nom}} \quad (2.30)$$

$E_{sp} = 50 \text{ kWh/kg}$

- The electrical power effectively consumed by the electrolyzer is :

$$P_{elec}(t) = \min(P_{pV} - W_{comp} ; P_{EL}) \quad (2.31)$$

- The compression work is calculated using the isentropic model:

$$W_{comp_1} = \frac{\gamma}{\gamma - 1} \cdot \frac{R \cdot T}{M_{H_2} \cdot \eta_{comp}} \cdot \left[ \left( \frac{P_{out}}{P_{in,H_2}} \right)^{\frac{\gamma}{\gamma-1}} - 1 \right] \cdot \frac{\dot{m}_{demand}}{3600} \quad (2.32)$$

$$W_{comp_2} = \frac{\gamma}{\gamma - 1} \cdot \frac{R \cdot T}{M_{N_2} \cdot \eta_{comp}} \cdot \left[ \left( \frac{P_{out}}{P_{in,N_2}} \right)^{\frac{\gamma}{\gamma-1}} - 1 \right] \cdot \frac{\dot{m}_{demand} \cdot 4.63}{3600} \quad (2.33)$$

$$W_{comp} = W_{comp_1} + W_{comp_2} \quad (2.34)$$

We assume :

- $P_{in,H_2} = 30 \text{ bar}$
- $P_{in,N_2} = 8 \text{ bar}$

The instantaneous hydrogen production mass flow rate is given by :

$$\dot{m}_{H_2}(t) = \frac{P_{elec}(t)}{E_{sp,eff}(x_L)} \quad (2.35)$$

- The activation condition for the electrolyzer is :

$$P_{net}(t) \geq x_{min} \cdot P_{EL} \quad (2.36)$$

The value of  $x_{min}$  is fixed at 0.05 (5%) based on manufacturer specifications.

## 2.4 Modeling of Hydrogen Storage

### 2.4.1 Role of the Storage Tank in the Process

The storage tank acts as a buffer system to smooth out the intermittent, solar-driven production of hydrogen, ensuring a steady, reliable mass flow feed to the downstream continuous chemical synthesis reactor.

### 2.4.2 Storage Management Logic

The mass balance equation governing the hydrogen storage level is defined as :

$$tank(t + \Delta t) = \min(C_{tank}, tank(t) + \Delta m_{excess} - \Delta m_{Stock \rightarrow Reactor}) \quad (2.37)$$

$$\Delta m_{excess} = \max(0, \dot{m}_{H_2}(t) \cdot \Delta t - \dot{m}_{demand} \cdot \Delta t) \quad (2.38)$$

$$\Delta m_{Stock \rightarrow Reactor} = \begin{cases} 0 & \text{if PV source is sufficient} \\ \dot{m}_{demand} \cdot \Delta t - \Delta m_{PV \rightarrow Reactor} & \text{if PV source isn't sufficient} \end{cases} \quad (2.39)$$

Where  $\Delta m_{PV \rightarrow Reactor}$  is the mass quantity of hydrogen supplied to the tank by the PV-powered electrolyzer system.

## 2.5 Modeling of Ammonia Synthesis (Haber-Bosch)

The stoichiometric mass ratio between the consumed hydrogen and the produced ammonia is calculated from their respective molecular weights :

$$\frac{m_{H_2}}{m_{NH_3}} = \frac{3 \times M_{H_2}}{2 \times M_{NH_3}} = \frac{3 \times 2.016}{2 \times 17.031} \approx 0.1775 \quad (2.40)$$

The instantaneous ammonia production mass flow rate is :

$$\dot{m}_{NH_3}(t) = \frac{\dot{m}_{demand}}{0.1775} \quad (2.41)$$

The annual production per wilaya is obtained by numerical integration over 365 days with a time step  $\Delta t$  :

$$Q_{NH_3} = \sum_{j=1}^{365} \sum_{t=0}^{T_{jour}} \dot{m}_{NH_3}(t) \cdot \Delta t \quad (2.42)$$

## 2.6 Techno-Economic Modeling

### 2.6.1 Cost Structure

The economic model distinguishes between two primary cost categories:

- **CAPEX (Capital Expenditure)** : The initial, upfront capital investments incurred at the beginning of the project ( $t = 0$ ). This encompasses the purchase and installation of the photovoltaic plant, electrolyzers, storage tanks, Haber-Bosch synthesis unit.
- **OPEX (Operational Expenditure)** : Recurring annual expenditures incurred throughout the operational lifetime of the facility.

The table below details the cost structure used for the techno-economic analysis. It distinguishes between capital expenditures (CAPEX) and operational expenditures (OPEX) for each subsystem

Table 2.1 : Cost structure

| expenditure items   | Designation   | Formulas                                                                                                                                                                                                                                                                                | Ref  |
|---------------------|---------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| PV Plant            | $C_{PV}$      | $C_{PV} = (C_{Mod} + C_{BOS} + C_{GC}) \cdot P_{EL} + C_{Terrain} \cdot S_{terrain} \quad (2.43)$                                                                                                                                                                                       | [13] |
|                     | $O_{PV}$      | $O_{PV} = 16 \text{ €/kWc/an}$                                                                                                                                                                                                                                                          |      |
| PEM Electrolyzer    | $C_{EL}$      | $C_{EL} = P_{EL} \cdot RC_{EL} \left( \frac{P_{EL}}{RP_{EL}} \right)^{SF_{EL}} \quad (2.44)$                                                                                                                                                                                            | [2]  |
|                     | $O_{EL}$      | $O_{EL} = C_{EL} \cdot 3.44\% \cdot P_{EL}^{-0.155} \quad (2.45)$                                                                                                                                                                                                                       |      |
| Compressor          | $C_{comp}$    | Accounting for generalized inflation via the US Consumer Price Index (CPI), the baseline capital expenditure for the modular compression train escalates from its 2013 vendor-quoted value of 515,000 \$ to approximately 740,600 \$ (629 510 €), based on a rated capacity of 33 kg/h. | [14] |
| Water Supply        | $O_{WS}$      | $O_{WS} = 0.97 \sum_{t=0}^{8760} V_{H_2O}(t) \quad (2.46)$<br>0.97 is the price of the water in €/m <sup>3</sup>                                                                                                                                                                        | [15] |
| Hydrogen storage    | $C_{st,H_2}$  | $C_{st,H_2} = 605 \text{ €/kg}$                                                                                                                                                                                                                                                         | [16] |
| Haber-Bosch Process | $C_{HB,ASU}$  | $C_{HB,ASU} = P_{EL} \cdot RC_{HB,ASU} \quad (2.47)$                                                                                                                                                                                                                                    | [2]  |
|                     | $O_{HB,ASU}$  | $O_{HB,ASU} = 1.5\% \cdot C_{HB,ASU} \quad (2.48)$                                                                                                                                                                                                                                      |      |
| Ammonia storage     | $C_{st,NH_3}$ | $C_{st,NH_3} = 2.59 \cdot cap_{st,NH_3} \quad (2.49)$<br>2.59 is the cost of ammonia storage in €/kg                                                                                                                                                                                    | [17] |

The table below complements the previous one by providing the numerical values of the parameters used in the cost equations.

Table 2.2 : Costs values

| Variables     | Significance                                    | Values                | References |
|---------------|-------------------------------------------------|-----------------------|------------|
| $C_{Mod}$     | Unit cost of PV modules                         | 515 €/kW              | [13]       |
| $C_{BOS}$     | Balance of System cost                          | 75 €/kW               |            |
| $C_{GC}$      | Civil engineering and site preparation cost     | 165 €/kW              |            |
| $C_{terrain}$ | Cost of land                                    | 0.13 €/m <sup>2</sup> |            |
| $S_{terrain}$ | Specific land area required                     | 10 m <sup>2</sup> /kW | [18]       |
| $RC_{EL}$     | Reference specific cost of the PEM electrolyzer | 600 €/kW              | [19]       |
| $RP_{EL}$     | Reference capacity of the PEM electrolyzer      | 10 MW                 |            |
| $SF_{EL}$     | Scaling factor for the PEM Electrolyzer         | -0.21                 |            |

## 2.6.2 LCOA calculation

$$LCOA = \frac{C_{total} + \sum_{t=0}^{T-1} \frac{O_{total}}{(1+r)^t}}{\sum_{t=0}^{T-1} \frac{Q_{NH_3}}{(1+r)^t}} \quad (2.50)$$

$Q_{NH_3}$ : The quantity of ammonia produced annually (typically measured in metric tons or kilograms).

T : The total lifetime of the project (in years).

r : Discount rate

$C_{total}$  : total CAPEX

$O_{total}$  : total OPEX



**CHAPTER 3 :  
DEVELOPMENT OF THE  
INTERACTIVE  
SIMULATION PLATFORM**

# CHAPTER 3 : DEVELOPMENT OF THE INTERACTIVE SIMULATION PLATFORM

## 3.1 Introduction

The primary objective of the simulation platform developed in this work is to provide a comprehensive, interactive tool to simulate, visualize, and analyze green ammonia production powered by solar photovoltaic (PV) energy across all 58 Algerian wilayas.

The specific objectives of this platform are to :

- **Provide an Intuitive Graphical Interface** : Enable engineers, researchers, and decision-makers to easily configure system parameters and evaluate design configurations.
- **Simulate Real-Time Dynamic Behavior** : Model the transient production behavior of green ammonia under variable, hourly solar irradiance profiles.
- **Perform Simultaneous Regional Assessment** : Calculate and visualize the annual ammonia production capacity for all 58 wilayas concurrently to facilitate comparative geographical analysis.
- **Evaluate Financial Viability** : Compute the Levelized Cost of Ammonia (LCOA) by integrating detailed capital expenditure (CAPEX) and operational expenditure (OPEX) variables.

## 3.2 Platform architecture

The structural architecture of the simulation platform is designed around a reactive, data-driven MVC (Model-View-Controller) paradigm. This architecture decouples the core scientific computing scripts from the front-end rendering engine.

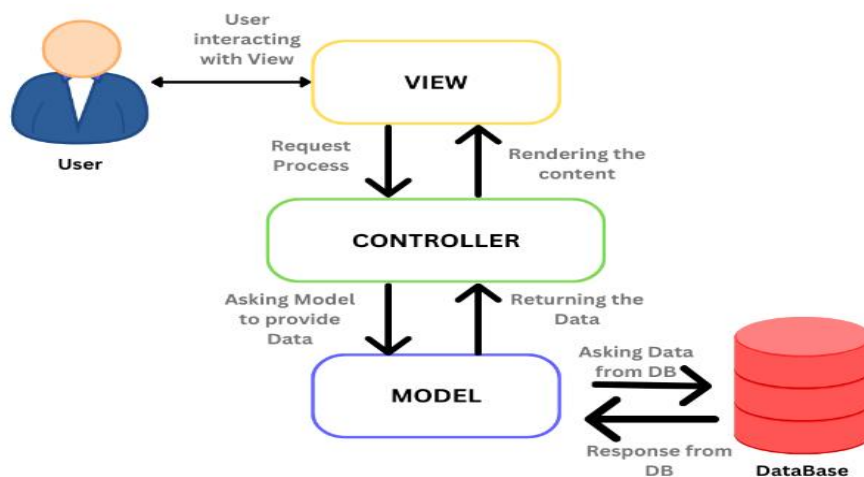


Figure 3.1 : The MVC structure

As a result, the application can simultaneously compute complex technical and economic equations across all 58 wilayas without causing user interface latency.

The diagram below details the structural interactions and data pathways within the platform :

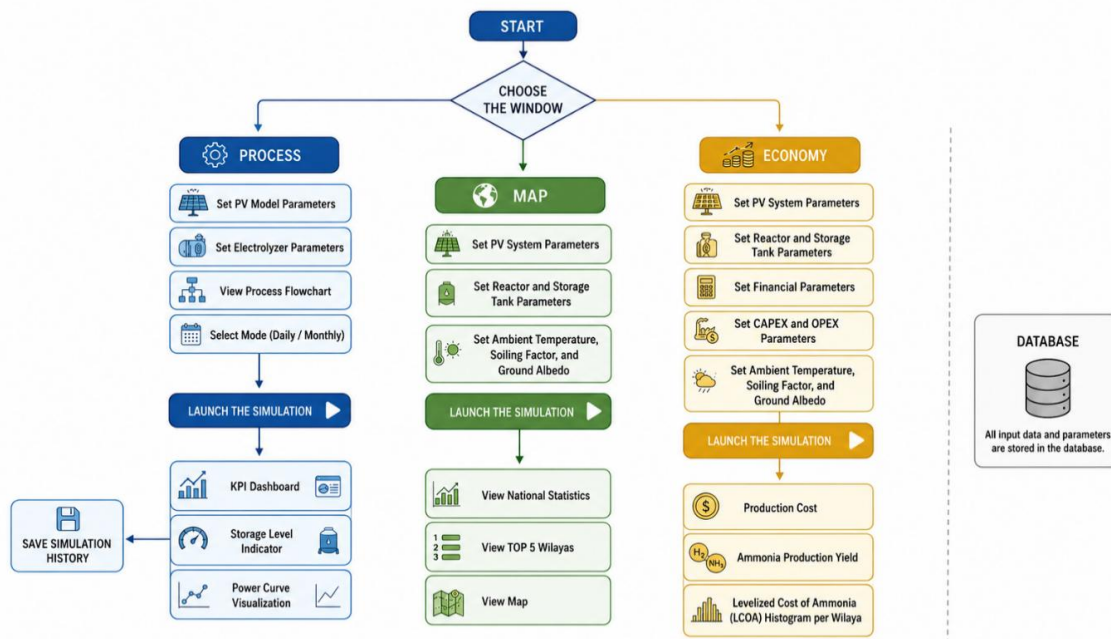


Figure 3.2 : General Web Application Flowchart

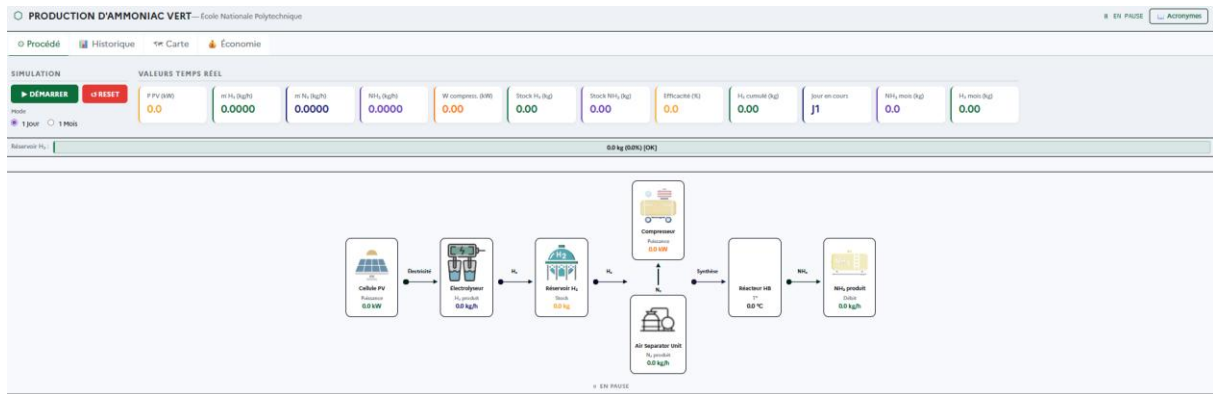
## 3.3 Windows presentation

### 3.3.1 Process diagram Tab

The table below summarises the configurations and features of the "Process" tab of the interactive platform.

Table 3.1 : Process diagram configuration

| Sub-tab / Feature        | Inputs                                                                                                                                                           | Outputs                                                                                                                                                                                                                                                                                                                                                                      | Python technologies                                                         |
|--------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| Simulation control       | <ul style="list-style-type: none"> <li>Start / Pause / Reset buttons</li> <li>Mode selector (1 day / 1 month)</li> <li>Month dropdown (if month mode)</li> </ul> | <ul style="list-style-type: none"> <li>Simulation clock (day/hour)</li> <li>Status indicator (Running/Paused)</li> </ul>                                                                                                                                                                                                                                                     | Dash (callbacks)<br><br>dcc.Store<br><br>dcc.Interval                       |
| Real Time KPIs           | /                                                                                                                                                                | <ul style="list-style-type: none"> <li>PV power (kW)</li> <li>Flow rates H<sub>2</sub>, N<sub>2</sub>, NH<sub>3</sub> (kg/h)</li> <li>Compressor power (kW)</li> <li>H<sub>2</sub> stock (kg)</li> <li>NH<sub>3</sub> stock (kg)</li> <li>Efficiency (%)</li> <li>Cumulative H<sub>2</sub> (kg)</li> <li>Simulated day, NH<sub>3</sub> month, H<sub>2</sub> month</li> </ul> | Dash (callbacks)<br><br>HTML update                                         |
| Animated Process diagram | <ul style="list-style-type: none"> <li>simulation values drive animation</li> </ul>                                                                              | <ul style="list-style-type: none"> <li>Process schematic (SVG icons)</li> <li>Flow animations (moving dots)</li> <li>Equipment glow when active</li> <li>H<sub>2</sub> tank gauge with threshold</li> </ul>                                                                                                                                                                  | dash_svg<br><br>custom CSS<br><br>client-side JavaScript (60 fps animation) |

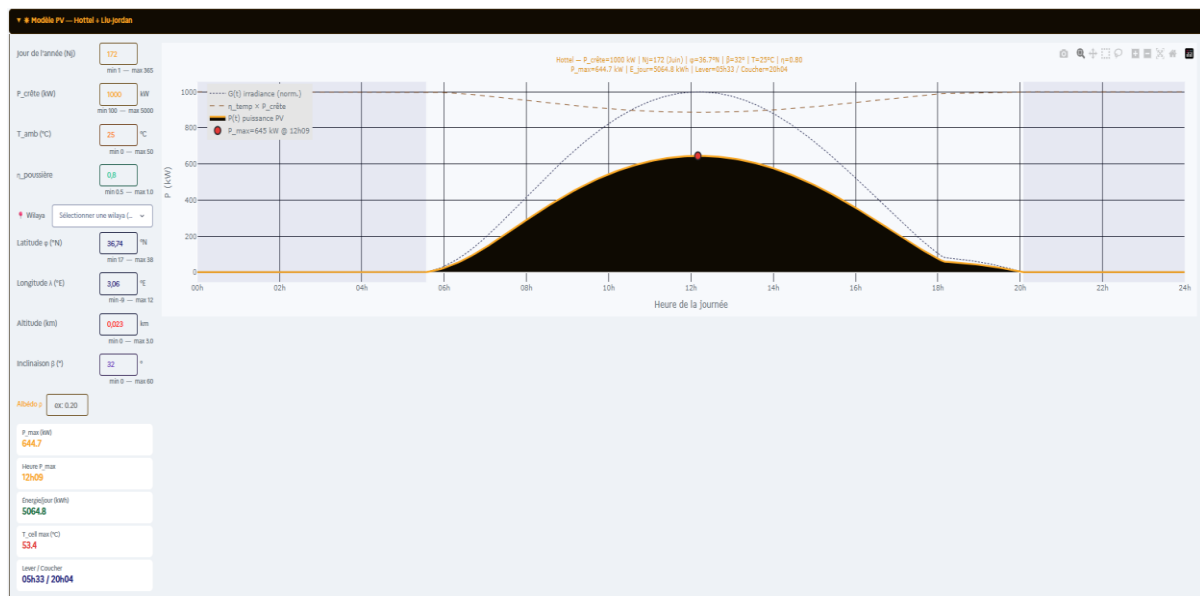


### 3.3.2 PV model Sub-Panel

The table below presents the adjustable parameters of the sub-panel dedicated to the photovoltaic model, It also specifies the generated graphs and the technologies used.

Table 3.2 : PV model sub-panel configuration

| Sub-tab / Feature | Inputs                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Outputs                                                                                                                                                                                                                                | Python technologies                                                                          |
|-------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|
| PV model          | <ul style="list-style-type: none"> <li>Day of year <math>N_j</math> (1-365)</li> <li>Peak power (Kw, 100-5000)</li> <li>Ambient temperature (<math>^{\circ}\text{C}</math>, 0-50)</li> <li>Dust factor (0.5-1.0)</li> <li>Wilaya selection (fills lat/lon/alt/<math>\beta</math>)</li> <li>Latitude <math>\phi</math> (<math>^{\circ}\text{N}</math>)</li> <li>Longitude <math>\lambda</math> (<math>^{\circ}\text{E}</math>)</li> <li>Altitude (km)</li> <li>Tilt angle <math>\beta</math> (<math>^{\circ}</math>)</li> <li>Albedo <math>\rho</math> (0-1)</li> </ul> | <ul style="list-style-type: none"> <li><math>P(t)</math> curve (irradiance, temperature, power)</li> <li>PV KPIs (<math>P_{\max}</math>, time of <math>P_{\max}</math>, daily energy, max cell temperature, sunrise/sunset)</li> </ul> | <p>Plotly (graph_objects)</p> <p>PV Model (Hottel + Liu-Jordan)</p> <p>numpy</p> <p>math</p> |



### 3.3.3 PEM Electrolyser Sub-Panel

The table below details the adjustable parameters of the PEM electrolyser sub-panel. Outputs include instantaneous and cumulative hydrogen production curves. This sub-panel allows the user to simulate the behaviour of the electrolyser under different load and sizing conditions.

Table 3.3 : PEM Electrolyser Sub-Panel configuration

| Sub-tab / Feature | Inputs                                                                                                                                                                                                                                                                                                        | Outputs                                                                                                                                                                                                 | Python technologies                                                                                                     |
|-------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|
| PEM electrolyser  | <ul style="list-style-type: none"> <li>Max electrolyser power (kW)</li> <li>Minimum load fraction (0.05-0.30)</li> <li>Specific energy (kWh/kg H<sub>2</sub>)</li> <li>H<sub>2</sub> tank capacity (kg)</li> <li>H<sub>2</sub> minimum threshold (kg)</li> <li>Reactor H<sub>2</sub> demand (kg/h)</li> </ul> | <ul style="list-style-type: none"> <li><math>\dot{m}_{H_2}(t)</math> and cumulative H<sub>2</sub> (kg)</li> <li>H<sub>2</sub> KPIs: daily H<sub>2</sub> production, potential NH<sub>3</sub></li> </ul> | <ul style="list-style-type: none"> <li>Plotly (subplots)</li> <li>PV Model and PEM electrolysis calculations</li> </ul> |

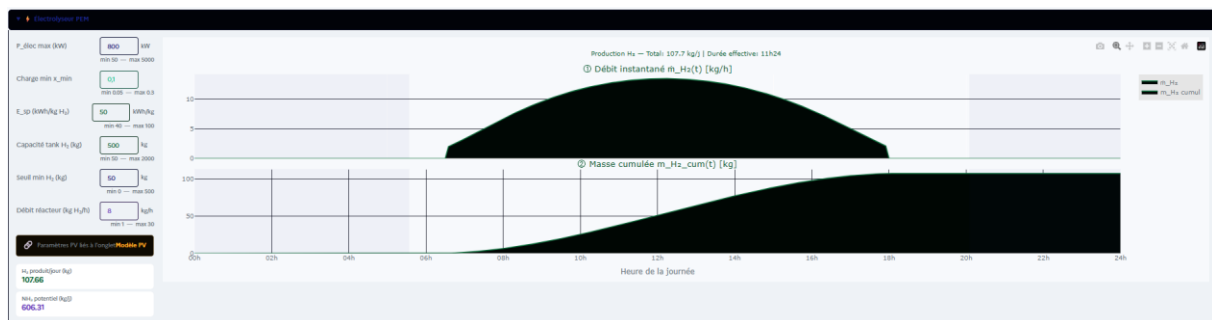


Figure 3.5 : PEM Electrolyser Sub-Panel

### Alarm System :

The table below defines the trigger conditions for the alarms integrated into the platform.

Table 3.4 : Alarm system

| Alarmer                    | Trigger Condition                       |
|----------------------------|-----------------------------------------|
| Empty H <sub>2</sub> Tank  | Tank = 0 and Electrolyzer is OFF        |
| Full H <sub>2</sub> Tank   | H <sub>2</sub> surplus cannot be stored |
| Low H <sub>2</sub> Warning | Tank < minimum threshold                |

### 3.3.4 Agricultural application

The table below summarises the parameters and outputs of the agricultural sub-panel

Table 3.5 : Agricultural application configuration

| Sub-tab / Feature        | Inputs                                                                                                        | Outputs                                                                                                                                                                                            | Python technologies                                                                                  |
|--------------------------|---------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|
| Agricultural application | <ul style="list-style-type: none"> <li>Area (ha, 1-500)</li> <li>Nitrogen demand (kg N/ha, 50-300)</li> </ul> | <ul style="list-style-type: none"> <li>Gauges: NH<sub>3</sub> stock vs requirement, covered area</li> <li>Agricultural KPIs: total NH<sub>3</sub> needed, available nitrogen, days left</li> </ul> | <ul style="list-style-type: none"> <li>Plotly (indicator)</li> <li>agronomic calculations</li> </ul> |



Figure 3.6 : Agricultural application

### 3.3.5 History Tab

The table below describes the "History" tab, which records the state variables of the simulation at each time step

Table 3.6 : History Tab configuration

| Sub-tab / Feature  | Inputs                                | Outputs                                                                                         | Python technologies                                                          |
|--------------------|---------------------------------------|-------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Simulation journal | – (simulation ticks feed the history) | – Table of state variables (time, PV power, electrolyser status, flows, stocks, reactor status) | Dash (callbacks)<br>dcc.Store<br>dynamic HTML table<br>30-day sliding window |
| Buttons            | – Clear journal<br>– Scroll to bottom | – Entry counter<br>– Updated table                                                              | Dash callbacks                                                               |

| t (s) | P <sub>pv</sub> (kW) | Electro | W <sub>el</sub> (kg/h) | Charge x (s) | P <sub>up</sub> off | Stock H <sub>2</sub> (kg) | H <sub>2</sub> P <sub>tot</sub> (kg) | H <sub>2</sub> 510-R | H <sub>2</sub> v51210-R | W <sub>el</sub> (kg/h) | q (s) | Reactor |
|-------|----------------------|---------|------------------------|--------------|---------------------|---------------------------|--------------------------------------|----------------------|-------------------------|------------------------|-------|---------|
| 11.59 | 580.4                | ON      | 11.9111                | 68.4         | 46.74               | 11.42                     | 0.0000                               | 0.0000               | 0.0000                  | 11.7917                | 18.7  | ON      |
| 11.60 | 570.6                | ON      | 11.9108                | 70.4         | 46.81               | 11.43                     | 0.0000                               | 0.0000               | 0.0000                  | 11.7917                | 18.3  | ON      |
| 11.61 | 561.3                | ON      | 11.9109                | 71.3         | 46.94               | 11.43                     | 0.0000                               | 0.0000               | 0.0000                  | 11.7917                | 18.9  | ON      |
| 11.62 | 550.2                | ON      | 11.9111                | 72.1         | 47.03               | 10.41                     | 0.0000                               | 0.0000               | 0.0000                  | 11.7917                | 18.6  | ON      |
| 11.70 | 580.7                | ON      | 11.9108                | 71.8         | 47.12               | 10.18                     | 0.0000                               | 0.0000               | 0.0000                  | 11.7917                | 18.3  | ON      |
| 11.80 | 600.6                | ON      | 11.9101                | 71.7         | 47.28               | 20.74                     | 0.0000                               | 0.0000               | 0.0000                  | 11.7917                | 18.6  | ON      |
| 11.90 | 600.5                | ON      | 11.9107                | 74.4         | 47.28               | 20.30                     | 0.0000                               | 0.0000               | 0.0000                  | 11.7917                | 18.7  | ON      |
| 11.99 | 611.7                | ON      | 11.9101                | 71.1         | 47.35               | 20.44                     | 0.0000                               | 0.0000               | 0.0000                  | 11.7917                | 18.4  | ON      |
| 11.99 | 611.6                | ON      | 11.9108                | 71.7         | 47.41               | 20.17                     | 0.0000                               | 0.0000               | 0.0000                  | 11.7917                | 18.2  | ON      |
| 11.99 | 611.1                | ON      | 11.9108                | 70.3         | 47.47               | 21.10                     | 0.0000                               | 0.0000               | 0.0000                  | 11.7917                | 18.6  | ON      |
| 11.99 | 611.1                | ON      | 11.9101                | 70.8         | 47.51               | 21.40                     | 0.0000                               | 0.0000               | 0.0000                  | 11.7917                | 17.8  | ON      |
| 11.99 | 610.7                | ON      | 11.9101                | 77.2         | 47.57               | 21.91                     | 0.0000                               | 0.0000               | 0.0000                  | 11.7917                | 17.7  | ON      |
| 11.99 | 610.8                | ON      | 11.9101                | 77.6         | 47.62               | 21.41                     | 0.0000                               | 0.0000               | 0.0000                  | 11.7917                | 17.5  | ON      |
| 11.99 | 610.8                | ON      | 11.9101                | 78.9         | 47.65               | 21.91                     | 0.0000                               | 0.0000               | 0.0000                  | 11.7917                | 17.4  | ON      |
| 11.70 | 610.1                | ON      | 11.9101                | 78.1         | 47.69               | 21.40                     | 0.0000                               | 0.0000               | 0.0000                  | 11.7917                | 17.1  | ON      |

Figure 3.7 : History tab

### 3.3.6 Map Tab

The table below presents the "Map" tab, which enables a comparative analysis of the 58 wilayas. It describes the inputs, the outputs and the per-wilaya adjustable parameters.

Table 3.7 : Map Tab configuration

| Sub-tab / Feature          | Inputs                                                                                                                                                                                                                                      | Outputs                                                                                                                                                                                                                                                               | Python technologies                                              |
|----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------|
| National map of 58 wilayas | – N <sub>j</sub><br>– Peak power per wilaya (kW)<br>– Specific energy (kWh/kg H <sub>2</sub> )<br>– Dust factor<br>– Reactor H <sub>2</sub> demand (kg/h)<br>– H <sub>2</sub> tank capacity (kg)<br>– H <sub>2</sub> minimum threshold (kg) | – Choropleth map (bubble size proportional to NH <sub>2</sub> /day)<br>– Tooltips per wilaya (NH <sub>2</sub> , H <sub>2</sub> , avoided CO <sub>2</sub> , solar hours)<br>– National statistics (total, average, avoided CO <sub>2</sub> , water)<br>– Top 5 wilayas | Plotly (Scattermap)<br>GeoJSON of wilayas<br>URL / cache loading |
| Per-wilaya parameters      | – T <sub>amb</sub> (°C)<br>– Albedo                                                                                                                                                                                                         | – Updated stores for the map                                                                                                                                                                                                                                          | dcc.Store<br>synchronisation callbacks                           |

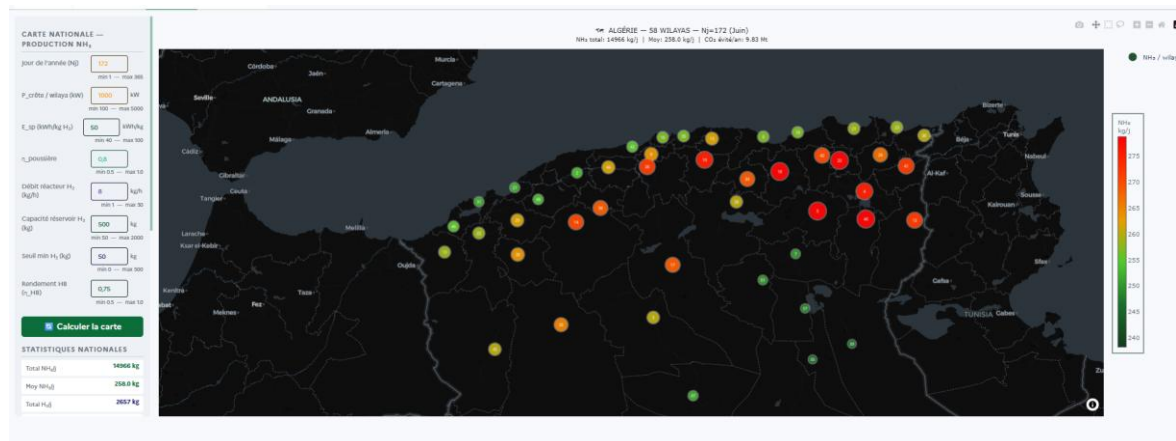


Figure 3.8 : Map Tab

### 3.3.7 Economy Tab

The table below synthesises the features of the "Economy" tab: technical parameters, financial parameters, editable CAPEX/OPEX tables, LCOA calculation, water cost, and comparative bar chart per wilaya.

Table 3.8 : Economy Tab configuration

| Sub-tab / Feature                                   | Inputs                                                                                                                                                                                                                                                                                                                                                                                                               | Outputs                                                                                                                                                                                                                                                            | Python technologies                                                                                                |
|-----------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|
| Technical parameters                                | <ul style="list-style-type: none"> <li>– Peak power per wilaya (kW)</li> <li>– Specific energy (kWh/kg H<sub>2</sub>) <ul style="list-style-type: none"> <li>– Dust factor</li> </ul> </li> <li>– Max electrolyser power (kW)</li> <li>– Minimum load fraction</li> <li>– Reactor H<sub>2</sub> demand (kg/h)</li> <li>– H<sub>2</sub> tank capacity (kg)</li> <li>– H<sub>2</sub> minimum threshold (kg)</li> </ul> | <ul style="list-style-type: none"> <li>– (used in LCOA calculation)</li> </ul>                                                                                                                                                                                     | <ul style="list-style-type: none"> <li>dash_core_components</li> <li>stores</li> </ul>                             |
| Financial parameters                                | <ul style="list-style-type: none"> <li>– Discount rate (%)</li> <li>– Lifetime (years)</li> <li>– Exchange rate € → DZD</li> </ul>                                                                                                                                                                                                                                                                                   | <ul style="list-style-type: none"> <li>– (used in LCOA calculation)</li> </ul>                                                                                                                                                                                     |                                                                                                                    |
| CAPEX / OPEX tables                                 | <ul style="list-style-type: none"> <li>– Add/delete rows</li> <li>– Label and amount (€ or €/year)</li> </ul>                                                                                                                                                                                                                                                                                                        | <ul style="list-style-type: none"> <li>– CAPEX / OPEX totals</li> <li>– Row store</li> </ul>                                                                                                                                                                       | <ul style="list-style-type: none"> <li>dcc.Store</li> <li>dynamic callbacks</li> <li>client-side totals</li> </ul> |
| Water & water supply cost                           | <ul style="list-style-type: none"> <li>– (reuses technical parameters)</li> </ul>                                                                                                                                                                                                                                                                                                                                    | <ul style="list-style-type: none"> <li>– Table of water consumption (m<sup>3</sup>/year) and cost per wilaya</li> <li>– Total water supply cost</li> </ul>                                                                                                         | Derived from H <sub>2</sub> production (15 L water / kg H <sub>2</sub> )                                           |
| LCOA calculation                                    | <ul style="list-style-type: none"> <li>– Calculate LCOA button</li> <li>– All above parameters</li> </ul>                                                                                                                                                                                                                                                                                                            | <ul style="list-style-type: none"> <li>– Mean, min, max LCOA (€/kg, DZD/kg)</li> <li>– NH<sub>3</sub> production table per wilaya (t/year, OPEX, avoided CO<sub>2</sub>, LCOA)</li> <li>– Bar chart of LCOA per wilaya with conventional reference line</li> </ul> | <ul style="list-style-type: none"> <li>numpy</li> <li>discounting,</li> <li>Plotly (bar + hline)</li> </ul>        |
| Ambient temperature, $f_{dust}$ , Albedo per wilaya | $T_{amb}$ , $f_{dust}$ , Albedo                                                                                                                                                                                                                                                                                                                                                                                      | Updated store for economic calculation                                                                                                                                                                                                                             | <ul style="list-style-type: none"> <li>dcc.Store</li> <li>callbacks</li> </ul>                                     |

**PRODUCTION D'AMMONIAC VERT** — Ecole Nationale Polytechnique

Procédé Historique Carte **Economie**

**\* SYSTÈME PV & ELECTROLYSEUR**

$P_{crbo}$  / wilaya (kW)  kW  
min 100 — max 5000

$E_{sp}$  (kWh/kg H<sub>2</sub>)  kWh/kg  
min 40 — max 100

$\eta$  possible    
min 0.5 — max 1.0

$P_{elec}$  max (kW)  kW  
min 50 — max 5000

Charge min ( $x_{min}$ )    
min 0.05 — max 0.2

**REACTEUR & RÉSERVOIR**

Débit réacteur (kg H<sub>2</sub>/h)  kg/h  
min 1 — max 30

Capacité réservoir H<sub>2</sub> (kg)  kg  
min 50 — max 2000

Séuil min H<sub>2</sub> (kg)  kg  
min 0 — max 500

Rendement H<sub>2</sub> ( $\eta_{H_2}$ )    
min 0.5 — max 1.0

Pression réacteur (bar)  bar  
min 50 — max 300

**PARAMÈTRES FINANCIERS**

Taux actualisation (%)  %  
min 1 — max 15

Durée de vie (ans)  ans  
min 10 — max 30

**CAPEX — Investissements initiaux (€)**

| Poste / Description                | Montant (€)      |
|------------------------------------|------------------|
| Centrale PV                        | 500000           |
| Électrolyseur PEM                  | 800000           |
| Compresseur                        | 100000           |
| Stockage H <sub>2</sub> (comprimé) | 25000            |
| Stockage NH <sub>3</sub>           | 50000            |
| Génie civil & raccordement         | 100000           |
| <b>Total</b>                       | <b>1925000 €</b> |

**OPEX — Charges annuelles (€/an)**

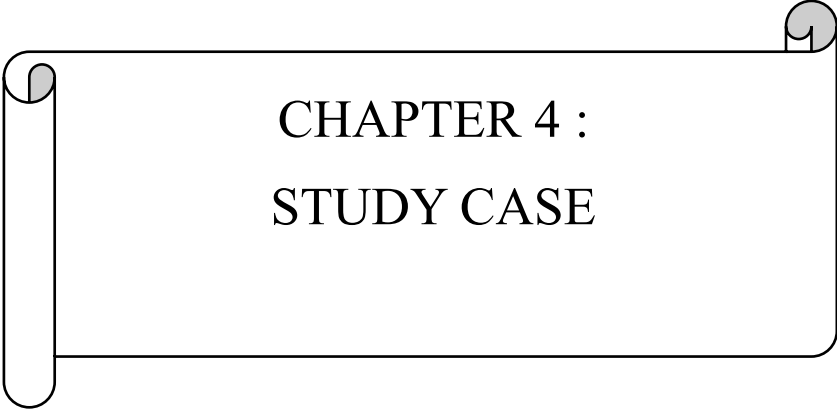
| Poste / Description       | Montant (€/an)     |
|---------------------------|--------------------|
| Eau de process            | 5000               |
| Transport NH <sub>3</sub> | 20000              |
| Maintenance (O&M)         | 32000              |
| Assurance                 | 8000               |
| Personnel                 | 48000              |
| <b>Total</b>              | <b>105000 €/an</b> |

Taux de change: 1 € = 136 DA (Donnée Algérie) 145 DA / €

Les résultats ci-dessous seront affichés en € et en DA

**Calculer le LCOA**

Figure 3.9 : Economy Tab



## CHAPTER 4 : STUDY CASE

# CHAPTER 4 : STUDY CASE

## 4.1 System Configuration

We consider this parameters represented in this table :

Table 4.1 : System configuration – Situation 1

| Parameters                          |                              | Values    |
|-------------------------------------|------------------------------|-----------|
| <b>PV System &amp; Electrolyser</b> | Peak power                   | 1000 kW   |
|                                     | Specific energy of PEM       | 50 kWh/kg |
|                                     | Nominal power of PEM         | 800 kW    |
|                                     | Min load                     | 0.05      |
| <b>Reactor &amp; Tank</b>           | Reactor feed                 | 8 kg/h    |
|                                     | Tank capacity                | 130 kg    |
|                                     | Min threshold.H <sub>2</sub> | 0 kg      |
| <b>Financial parameters</b>         | discount rate                | 12 %      |
|                                     | Life time                    | 10 years  |

The table below details the costs associated with the base configuration ( situation 1 )

Table 4.2 : Cost configuration – Situation 1

| expenditure items   | Designation   | Value                                                                      |
|---------------------|---------------|----------------------------------------------------------------------------|
| PV Plant            | $C_{PV}$      | 756 800 €                                                                  |
|                     | $O_{PV}$      | 16 000 €/an                                                                |
| PEM Electrolyser    | $C_{EL}$      | 815 816 €                                                                  |
|                     | $O_{EL}$      | 9 842 €/an                                                                 |
| Compressor          | $C_{comp}$    | $629\,510 \cdot \left(\frac{8}{33}\right)^{0.77[20]} = 211\,410 \text{ €}$ |
| Water supply        | $O_{WTP}$     | $0.97 \sum_{t=0}^{8760} V_{H_2O}(t)$                                       |
| Hydrogen storage    | $C_{st,H_2}$  | $C_{st,H_2} = 605 \cdot 130 = 62\,624 \text{ €}$                           |
| Haber-Bosch process | $C_{HB,ASU}$  | 340 000 €                                                                  |
|                     | $O_{HB,ASU}$  | 5 100 €/an                                                                 |
| Ammonia storage     | $C_{st,NH_3}$ | $C_{st,NH_3} = 2.59 \cdot 1000 = 2\,590 \text{ €}$                         |

$$Total\ capex = 2\,189\,240 \text{ €} = 313\,061\,320 \text{ DA}$$

## 4.2 Results

We take in consideration 3 representatives wilayas : ( you will find the full results in the appendices section )

The table below presents the simulation results for the three representative wilayas (Djelfa, Tipaza, Adrar) in the base configuration ( situation 1 )

Table 4.3 : Results – Situation 1

| Wilaya | Ammonia Production (t/an) | Water supply (m³/an) | CO2 avoided (t/an) | LCOA (€/kg ) | LCOA (DA/kg ) |
|--------|---------------------------|----------------------|--------------------|--------------|---------------|
| Djelfa | 220.5                     | 588.1                | 397                | 1.709        | 247.8         |
| Tipaza | 195.8                     | 522.3                | 352.5              | 1.9248       | 279.1         |
| Adrar  | 154.3                     | 411.7                | 277.7              | 2.4427       | 354.2         |

### 4.3 Discussion

The results obtained for the three representative wilayas : Djelfa, Tipaza, and Adrar, demonstrate that the performance of a decentralized green ammonia production system is strongly influenced by local climatic conditions and photovoltaic energy availability.

Among the selected locations, Djelfa achieves the highest annual ammonia production of 220.5 t/year, followed by Tipaza with 195.8 t/year and Adrar with 154.3 t/year. A similar trend is observed for water consumption and avoided CO<sub>2</sub> emissions, since both quantities are directly linked to the amount of ammonia produced. Higher ammonia production requires more hydrogen from electrolysis and therefore more water.

At first glance, the lower production obtained in Adrar may appear surprising given its exceptional solar resource. However, solar irradiation alone does not determine the performance of a photovoltaic-powered ammonia production system. Ambient temperature and dust accumulation must also be considered. In desert environments, PV modules operate at significantly higher temperatures, which reduces their electrical efficiency. The decrease in module efficiency limits the electrical power delivered to the electrolyser, thereby reducing hydrogen and ammonia production.

Furthermore, dust deposition on photovoltaic panels represents a major source of performance degradation in southern Algeria. Frequent dust events and airborne sand particles reduce the transmittance of the PV module surface and decrease the amount of solar radiation converted into electricity. As a result, part of the theoretical solar potential of Adrar cannot be effectively exploited unless appropriate cleaning and maintenance strategies are implemented. The combined effects of high temperatures and soiling losses can therefore explain why Adrar exhibits lower ammonia production despite receiving some of the highest solar irradiation levels in the country.

In contrast, Djelfa benefits from a more balanced climatic profile. While its solar irradiation is slightly lower than that of the southern desert regions, the moderate temperatures and lower soiling rates improve the overall performance of the photovoltaic system. Consequently, a greater fraction of the available solar resource is converted into useful electrical energy, leading to higher electrolyzer utilization and increased ammonia production. This favorable operating environment contributes to the best overall system performance among the studied cases.

Tipaza occupies an intermediate position. The coastal climate provides relatively moderate temperatures, which are beneficial for PV operation, but the available solar resource is lower than in the inland and southern regions. As a result, ammonia production and environmental benefits remain lower than those achieved in Djelfa, while the production cost is slightly higher.

The economic analysis confirms the strong dependence of the Levelized Cost of Ammonia (LCOA) on annual production. Djelfa presents the lowest LCOA at 1.709 €/kg (247.8 DA/kg), whereas Tipaza and Adrar reach 1.9248 €/kg (279.1 DA/kg) and 2.4427 €/kg (354.2 DA/kg), respectively. Since the capital investment associated with the PV plant, electrolyzer, nitrogen production unit, and ammonia synthesis loop represents a substantial share of the total cost, higher annual production allows these fixed costs to be distributed over a larger quantity of ammonia. Consequently, locations achieving greater production exhibit lower specific production costs.

From an environmental perspective, all three wilayas demonstrate significant decarbonization potential. The avoided CO<sub>2</sub> emissions range from 277.7 t/year in Adrar to 397 t/year in Djelfa,

illustrating the ability of green ammonia to replace conventionally produced ammonia derived from fossil fuels. Although the differences in avoided emissions primarily reflect differences in ammonia output, the results confirm the environmental benefits associated with the deployment of renewable-energy-based ammonia production systems.

Overall, the analysis highlights that the optimal location for decentralized green ammonia production is not necessarily the site with the highest solar irradiation. Instead, system performance results from the combined effects of solar resource availability, ambient temperature, dust accumulation, and equipment utilization. Among the representative wilayas considered, Djelfa offers the most favorable balance between technical performance, economic competitiveness, and environmental benefits, while Adrar illustrates the challenges associated with operating photovoltaic-based industrial systems under harsh desert conditions.

#### 4.4 Sensitivity Analysis – Impact of PV Peak Power

To assess the impact of system scale on the techno-economic performance of decentralised green ammonia production, a sensitivity analysis was performed by **varying only the PV peak power** from 1000 kW (Situation 1) to 2000 kW (Situation 2). All other parameters : electrolyser capacity, reactor feed, storage capacity, financial parameters, and cost structure remained unchanged.

This analysis directly addresses the question: *"What is the effect of scaling up the PV system on ammonia production and LCOA ?"*

The table below presents the second system configuration (Situation 2), where the PV peak power is doubled to 2000 kW.

Table 4.4 : System configuration – Situation 2

| Parameters                          |                              | Values    |
|-------------------------------------|------------------------------|-----------|
| <b>PV System &amp; Electrolyser</b> | Peak power                   | 2000 kW   |
|                                     | Specific energy of PEM       | 50 kWh/kg |
|                                     | Nominal power of PEM         | 800 kW    |
|                                     | Min load                     | 0.05      |
| <b>Reactor &amp; Tank</b>           | Reactor feed                 | 8 kg/h    |
|                                     | Tank capacity                | 130 kg    |
|                                     | Min threshold.H <sub>2</sub> | 0 kg      |
| <b>Financial parameters</b>         | discount rate                | 12 %      |
|                                     | Life time                    | 10 years  |

The table below details the costs associated with the 2000 kW PV configuration.

Table 4.5 : Cost configuration – Situation 2

| expenditure items   | Designation   | Value                                                                      |
|---------------------|---------------|----------------------------------------------------------------------------|
| PV Plant            | $C_{PV}$      | 1 513 600 €                                                                |
|                     | $O_{PV}$      | 32 000 €/an                                                                |
| PEM Electrolyser    | $C_{EL}$      | 815 816 €                                                                  |
|                     | $O_{EL}$      | 9 842 €/an                                                                 |
| Compressor          | $C_{comp}$    | $629\,510 \cdot \left(\frac{8}{33}\right)^{0.77[20]} = 211\,410 \text{ €}$ |
| Water supply        | $O_{WTP}$     | $0.97 \sum_{t=0}^{8760} V_{H_2O}(t)$                                       |
| Hydrogen storage    | $C_{st,H_2}$  | $C_{st,H_2} = 605 \cdot 130 = 62\,624 \text{ €}$                           |
| Haber-Bosch process | $C_{HB,ASU}$  | 340 000 €                                                                  |
|                     | $O_{HB,ASU}$  | 5 100 €/an                                                                 |
| Ammonia storage     | $C_{st,NH_3}$ | $C_{st,NH_3} = 2.59 \cdot 1000 = 2\,590 \text{ €}$                         |

$$Total\ capex = 2\ 946\ 040\ \text{€} = 427\ 175\ 800\ DA$$

The table below presents the simulation results for the three representative wilayas (Djelfa, Tipaza, Adrar) in the base configuration ( situation 2 )

Table 4.6 : Results – Situation 2

| Wilaya | Ammonia Production (t/an) | Water supply (m³/an) | CO2 avoided (t/an) | LCOA (€/kg ) | LCOA (DA/kg ) |
|--------|---------------------------|----------------------|--------------------|--------------|---------------|
| Djelfa | 307                       | 818.3                | 552.6              | 1.6694       | 242.1         |
| Tipaza | 292.7                     | 780.2                | 526.8              | 1.751        | 253.9         |
| Adrar  | 270.9                     | 722.3                | 487.7              | 1.8916       | 274.3         |

### Impact on Ammonia Production :

The table below compares the increase in ammonia production between Situation 1 and Situation 2

Table 4.7 : Impact of PV Peak Power on ammonia production

| Wilaya | Ammonia Production (t/an)<br>Scenario 1 : 1MW | Ammonia Production (t/an)<br>Scenario 2 : 2 MW | Increase ( % ) |
|--------|-----------------------------------------------|------------------------------------------------|----------------|
| Djelfa | 220.5                                         | 307                                            | + 39           |
| Tipaza | 195.8                                         | 292.7                                          | + 49           |
| Adrar  | 154.3                                         | 270.9                                          | +76            |

- **Adrar shows the largest production increase (+76%)** because the higher solar irradiation in the Sahara is better exploited at larger scale.
- **Djelfa shows the smallest production increase (+39%)** because its performance is already relatively high at 1000 kW; the benefits of additional PV capacity are partially limited by the fixed electrolyser capacity (800 kW).
- **Tipaza shows an intermediate increase (+49%)** reflecting its coastal climate and moderate solar resource.

### Impact on LCOA :

The table below presents the LCOA reduction achieved by doubling PV capacity.

Table 4.8 : Impact of PV Peak Power on LCOA

| Wilaya | LCOA (€/kg )<br>Scenario 1 : 1MW | LCOA (€/kg )<br>Scenario 2 : 2 MW | Reduction ( % ) |
|--------|----------------------------------|-----------------------------------|-----------------|
| Djelfa | 1.709                            | 1.6694                            | -2.3            |
| Tipaza | 1.9248                           | 1.751                             | -8.2            |
| Adrar  | 2.4427                           | 1.8916                            | -22.4           |

- **Adrar shows the largest LCOA reduction (–22.4%)** because the additional PV capacity significantly increases production, spreading fixed costs over a larger output.
- **Djelfa shows the smallest LCOA reduction (–2.3%)** because the electrolyser capacity (800 kW) becomes the bottleneck; further increases in PV power without increasing electrolyser capacity yield diminishing returns.
- **Tipaza shows an intermediate reduction (–8.2%).**

### **The sensitivity analysis reveals several important findings :**

1. Scaling up PV capacity significantly increases ammonia production across all wilayas, with Adrar showing the largest increase (+76%) . This is because the higher solar irradiation in the Sahara is better exploited at larger scale, partially offsetting the thermal and soiling penalties. In contrast, Djelfa shows the smallest increase (+39%) , as its performance is already relatively high at 1000 kW, and the fixed electrolyser capacity (800 kW) becomes a bottleneck.
2. Scaling up PV capacity reduces LCOA, with Adrar benefiting most (−22.4%) . This confirms that economies of scale are most beneficial in high-irradiation, harsh-climate locations. The smaller reduction in Djelfa (−2.3%) indicates that further scaling without increasing electrolyser capacity yields diminishing returns.
3. The electrolyser capacity is a critical bottleneck. At 2000 kW PV, the 800 kW electrolyser limits production in Djelfa, where the additional solar energy cannot be fully converted into hydrogen. This suggests that scaling up should be accompanied by a proportional increase in electrolyser capacity to maximise the benefits of additional PV generation.

## **4.5 Conclusion**

This study evaluated the techno-economic and environmental performance of a decentralised green ammonia production system based on photovoltaic energy, PEM electrolysis, and the Haber–Bosch process, using three representative Algerian wilayas : Djelfa, Tipaza, and Adrar.

The results clearly show that annual ammonia production, water consumption, and CO<sub>2</sub> avoidance are strongly correlated and directly dependent on the effective use of solar energy. Among the three locations, Djelfa achieves the best overall performance with the highest production, the lowest Levelised Cost of Ammonia, and the greatest avoided emissions. Tipaza follows with moderate figures, while Adrar, despite having the highest solar irradiation, yields the lowest production and the highest LCOA.

The paradox of Adrar's underperformance is explained by adverse climatic factors : high ambient temperatures that reduce PV efficiency and severe dust accumulation (soiling) that further degrades energy yield. These findings demonstrate that solar irradiation alone is not a sufficient indicator for siting industrial-scale green ammonia plants. A balanced assessment of temperature, dust levels, water availability, and operational constraints is essential.

From an economic perspective, the large gap in LCOA between the three wilayas highlights the importance of capacity factor and plant utilisation. Higher annual production dilutes fixed capital costs, directly improving competitiveness. The environmental benefit, measured as avoided CO<sub>2</sub> emissions, confirms the significant decarbonisation potential of green ammonia, even at modest scales.

In conclusion, Djelfa emerges as the most favourable candidate among the three wilayas for a pilot or first-of-a-kind green ammonia facility, thanks to its balanced climate, moderate soiling, and good solar resource. Adrar would require additional technological measures (active cooling, automated cleaning) to become competitive. More generally, the methodology and results provide a replicable framework for pre-feasibility studies of green ammonia production across

Algeria's diverse climatic zones, supporting the country's strategy for renewable hydrogen and sustainable fertiliser production.

## 4.6 General conclusion

This thesis focused on the study and design of a decentralised green ammonia production system powered by solar photovoltaic energy, intended for agricultural applications in Algeria. The main achievements of this work are:

- **Modelling of the complete production chain** : Established mathematical models from the literature were implemented for solar PV generation (Hottel + Liu-Jordan), PEM electrolysis (linear ohmic model), hydrogen storage (threshold-based buffer), and Haber-Bosch synthesis, and then integrated into an interactive simulation platform for the 58 Algerian wilayas.
- **Techno-economic modelling** : Capital expenditures (CAPEX) and operational expenditures (OPEX) were quantified for each subsystem (PV plant, PEM electrolyser, compressor, hydrogen and ammonia storage, Haber-Bosch unit, air separation unit). Water supply costs (0.97 €/m<sup>3</sup>) were integrated, and the Levelised Cost of Ammonia (LCOA) was calculated using a discounted cash flow method over a 10-year lifetime with a 12 % discount rate.
- **Development of an interactive simulation platform** : A web-based dashboard was built using Dash/Plotly, featuring :
  - Real-time simulation with animated process diagram, KPIs, and alarm system.
  - Adjustable parameters for PV, electrolyser and agricultural demand
  - A national map of the 58 wilayas displaying daily ammonia production, water consumption and avoided CO<sub>2</sub>.
  - A techno-economic tab allowing users to edit CAPEX/OPEX tables, exchange rates, and compute LCOA.
- **Case study on three representative wilayas** : Djelfa, Tipaza, and Adrar were selected to illustrate the influence of local climate (solar irradiation, ambient temperature, dust accumulation) on system performance.

Djelfa achieved the highest annual ammonia production, the lowest LCOA, and the greatest CO<sub>2</sub> avoidance. Adrar, despite the highest solar irradiation, gave the lowest production and highest LCOA due to high temperatures (reducing PV efficiency) and severe dust soiling. Tipaza showed intermediate performance.

While the platform successfully demonstrates the feasibility of decentralised green ammonia production, several improvements and extensions are recommended for future research:

- **Incorporate real weather variability** : Replace the clear-sky assumption with stochastic or satellite-derived solar data to model cloud cover and daily fluctuations more realistically.
- **Scale up to industrial size** : Extend the model to multi-MW or GW-scale plants to assess export potential and economies of scale, particularly for green ammonia as a maritime fuel or for European markets.

- **Integrate wind energy** : Combine solar PV with wind power (especially in highland and coastal zones) to increase capacity factor and reduce LCOA.
- **Detailed water logistics** : Model water transport distance, pumping energy, and desalination costs instead of using a flat water price. Incorporate energy requirements for treated wastewater reuse.
- **Experimental validation** : Validate the PV and electrolyser sub-models with measured data from Algerian pilot plants (e.g., CDER in Ghardaïa or Adrar) to calibrate temperature, dust, and soiling coefficients.
- **Multi-objective optimisation** : Optimise system sizing (PV power, electrolyser capacity, storage volume) to minimise LCOA or maximise self-sufficiency under real solar profiles.
- **Lifecycle assessment (LCA)** : Extend the environmental analysis to include embodied emissions of equipment, water treatment impacts, and end-of-life recycling.
- **Agricultural demand integration** : Link the simulation to crop calendars and fertiliser requirement forecasts to design just-in-time ammonia production for local farming.
- **User-friendly enhancements** : Add interactive tutorials, PDF/Excel report export, and real-time weather API integration to make the platform more practical for policymakers and farmers.

This thesis has provided a comprehensive framework for the pre-feasibility study of decentralised green ammonia production from photovoltaic energy across Algeria. The developed simulation platform is a practical, open-source tool that can help engineers and decision-makers compare 58 wilayas, understand the impact of local climate, and estimate the Levelised Cost of Ammonia under various techno-economic scenarios.

The case study clearly demonstrates that solar irradiation alone is not a sufficient indicator for site selection. A balanced assessment of ambient temperature, dust levels, water availability, and operational constraints is essential. Djelfa emerges as the most favourable location among the three studied wilayas, while Adrar would require additional mitigation measures (active cooling, automated cleaning) to become competitive.

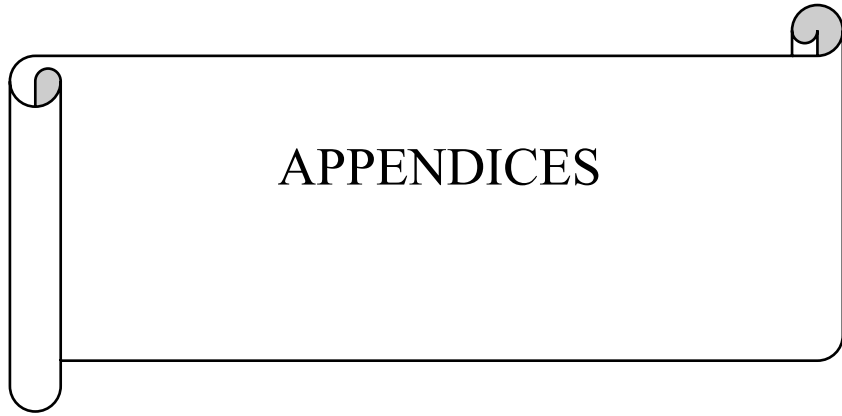
The sensitivity analysis confirms that scale is a critical lever for cost reduction, and that electrolyser capacity must be scaled proportionally with PV capacity to avoid bottlenecks. These findings provide clear guidance for policymakers and investors : prioritise low-cost financing, larger plants, and optimal site selection to maximise the competitiveness of green ammonia in Algeria.

More generally, the methodology and results support Algeria's national strategy for green hydrogen and sustainable fertiliser production. By valorising the country's exceptional solar resources in a smart, climate-aware manner, green ammonia can contribute to agricultural resilience, industrial decarbonisation, and new export opportunities in a low-carbon future.

# Bibliography

- [1] International Energy Agency (IEA), *Ammonia Technology Roadmap*, 2021. Available: <https://www.iea.org/reports/ammonia-technology-roadmap>
- [2] M. Monteiro Maia, “Techno-economic Analysis of Green Ammonia Production using Offshore Wind Farms,” Master’s thesis, Iceland School of Energy, Reykjavik, Iceland, 2021. Available: [https://skemman.is/bitstream/1946/39443/1/MSC-Mariana%20Monteiro%20Maia-2021\\_Final%20Signed.pdf](https://skemman.is/bitstream/1946/39443/1/MSC-Mariana%20Monteiro%20Maia-2021_Final%20Signed.pdf)
- [3] International Energy Agency (IEA), *Global Hydrogen Review 2025*, 2025. Available: <https://iea.blob.core.windows.net/assets/12d92ecc-e960-40f3-aff5-b2de6690ab6b/GlobalHydrogenReview2025.pdf>
- [4] Ministère de l’Énergie et des Mines, *Stratégie nationale de développement de l’hydrogène vert en Algérie*, 2023. Available: [https://www.oilmines.gov.dz/Media/galerie/doc\\_strategie\\_nationale\\_hydrogene\\_v.f\\_r\\_\(sept.2023\)\\_65b65e6f0b8eb.pdf](https://www.oilmines.gov.dz/Media/galerie/doc_strategie_nationale_hydrogene_v.f_r_(sept.2023)_65b65e6f0b8eb.pdf)
- [5] R. Boudries-Khellaf, “Etude d’un Système de Production d’Hydrogène Solaire en Algérie,” CDER, 2002. Available: [https://www.cder.dz/vlib/revue/nspeciauxpdf/za\\_3.pdf](https://www.cder.dz/vlib/revue/nspeciauxpdf/za_3.pdf)
- [6] T. Guessas, M. Boudrama, and L. Guettaf, “The Problem of Water Resources in Algeria: Assessment of the Current Situation and Proposal of Suitable Solutions,” University Farhat Abbas Setif1, 2024. Available: <https://asjp.cerist.dz/en/article/261375>
- [7] L. Bouchaala, N. Charchar, and A. E. Gherib, “Ressources hydriques: traitement et réutilisation des eaux usées en Algérie,” Division Biotechnologies et Environnement, Centre de Recherche en Biotechnologies (C.R.Bt), Constantine, Algeria, 2017. Available: <https://asjp.cerist.dz/en/article/40098>
- [8] A. Adda, W. M. Naceur, and M. Abbas, “Modélisation et optimisation de la consommation d’énergie d’une station de dessalement par procédé d’osmose inverse en Algérie,” *Revue des Energies Renouvelables*, vol. 19, no. 2, pp. 157–164, 2016. Available: <https://revue.cder.dz/index.php/rer/article/view/557/1241>
- [9] M. E. Sahin, “An Overview of Different Water Electrolyzer Types for Hydrogen Production,” *Energies*, vol. 17, no. 19, p. 4944, 2024. Available: <https://ideas.repec.org/a/gam/jeners/v17y2024i19p4944-d1491342.html>
- [10] L. Mulky et al., “An overview of hydrogen storage technologies – Key challenges and opportunities,” n.d. Available: <https://umpir.ump.edu.my/id/eprint/42578/1/An%20overview%20of%20hydrogen%20storage%20technologies.pdf>
- [11] W. Li, H. Tian, L. Ma, Y. Wang, X. Liu, and X. Gao, “Low-temperature water electrolysis: fundamentals, progress, and new strategies,” *Materials Advances*, vol. 3, pp. 5597–5613, 2022. Available: <https://pubs.rsc.org/en/content/articlepdf/2022/ma/d2ma00185c>
- [12] E. Esposito, A. Minotti, E. Fontananova, M. Longo, J. C. Jansen, and A. Figoli, “Green H<sub>2</sub> Production by Water Electrolysis Using Cation Exchange Membrane: Insights on Activation and Ohmic Polarization Phenomena,” *Membranes*, vol. 12, no. 1, p. 15, 2022. Available: <https://www.mdpi.com/2077-0375/12/1/15>

- [13] S. Cheref, “Etude et dimensionnement technico-économique d’une centrale photovoltaïque de 50 MW raccordée au réseau électrique à GUERRARA (GHARDAIA),” Master’s thesis, École Nationale Polytechnique, Algiers, Algeria, 2021.  
Available: <https://repository.enp.edu.dz/jspui/bitstream/123456789/10449/1/CHEREF.Sarah.pdf>
- [14] G. Parks, R. Boyd, J. Cornish, and R. Remick, “Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs,” National Renewable Energy Laboratory, NREL Report, 2014. Available: <https://docs.nrel.gov/docs/fy14osti/58564.pdf>
- [15] S. Drenkard and A. Mirakyan, “Étude exploratoire sur le potentiel du Power-to-X (hydrogène vert) pour l’Algérie,” 2021. Available: [https://energypartnership-algeria.org/fileadmin/algeria/21\\_12\\_07\\_Hydrog%C3%A8ne\\_vert\\_en\\_Alg%C3%A9rie\\_-\\_Rapport\\_PE.pdf](https://energypartnership-algeria.org/fileadmin/algeria/21_12_07_Hydrog%C3%A8ne_vert_en_Alg%C3%A9rie_-_Rapport_PE.pdf)
- [16] T. Jenkin, “Hydrogen production and the role of infrastructure: mainly storage and transport related,” 2024.  
Available: [https://www.esmap.org/sites/default/files/2022/Presentations/February\\_22\\_2024\\_v2.1\\_Hydrogen\\_and\\_role\\_of\\_storage\\_and\\_transportation\\_related\\_infrastructure\\_DRAFT.pdf](https://www.esmap.org/sites/default/files/2022/Presentations/February_22_2024_v2.1_Hydrogen_and_role_of_storage_and_transportation_related_infrastructure_DRAFT.pdf)
- [17] R. M. Nayak-Luke, C. Forbes, Z. Cesaro, R. Banares-Alcantara, and K. H. R. Rouwenhorst, “Techno-Economic Aspects of Production, Storage and Distribution of Ammonia,” in *Techno-Economic Challenges of Green Ammonia as an Energy Vector*, Elsevier, 2021.  
Available: [https://ris.utwente.nl/ws/portalfiles/portal/276441421/3\\_s2.0\\_B9780128205600000084\\_main.pdf](https://ris.utwente.nl/ws/portalfiles/portal/276441421/3_s2.0_B9780128205600000084_main.pdf)
- [18] Ministère de l’Écologie, du Développement durable, des Transports et du Logement, “Installations photovoltaïques au sol, Guide de l’étude d’impact,” 2011.  
Available: [https://www.ecologie.gouv.fr/sites/default/files/documents/Guide\\_EI\\_Installations-photovolt-au-sol\\_DEF\\_19-04-11.pdf](https://www.ecologie.gouv.fr/sites/default/files/documents/Guide_EI_Installations-photovolt-au-sol_DEF_19-04-11.pdf)
- [19] A. Singlitico, J. Østergaard, and S. Chatzivasileiadis, “Green Hydrogen from Offshore Wind Power Hubs,” 2021.  
Available: [http://www.chatziva.com/publications/2021\\_Singlitico\\_full.pdf](http://www.chatziva.com/publications/2021_Singlitico_full.pdf)
- [20] J. Lainé Arrate, “Small-scale green ammonia production plant: preliminary design and simulation using Aspen Plus,” Bachelor’s thesis, Escuela Técnica Superior de Ingenieros, Universidad de Cantabria, Spain, 2022.  
Available: <https://repositorio.unican.es/xmlui/bitstream/handle/10902/24744/440803.pdf?sequence=1&isAllowed=y>



## APPENDICES

# APPENDICES

## Appendix A

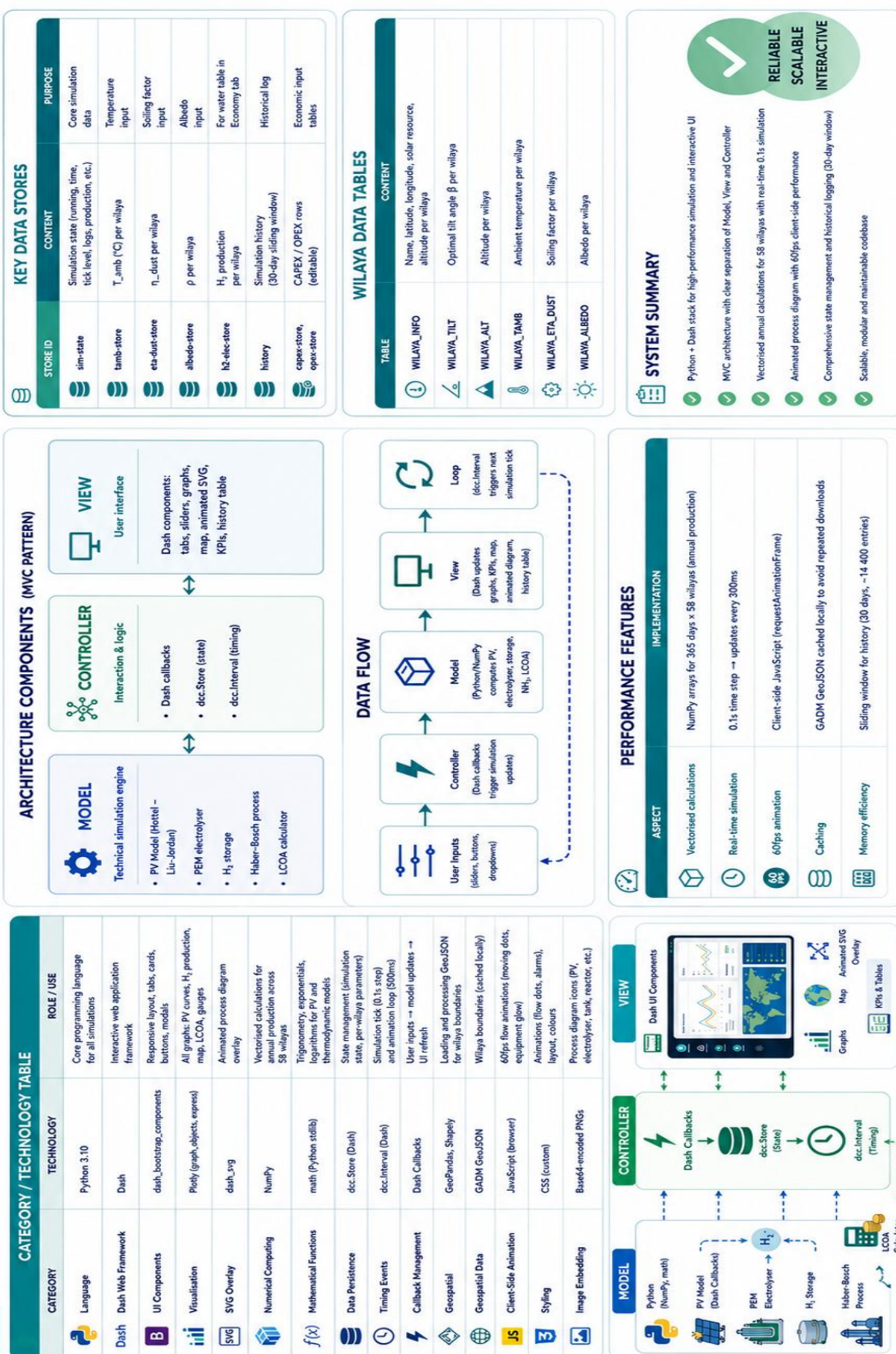
### Data wilaya information

The table below presents the data wilaya information used in our simulation

Table A.1 : Data wilaya information

| Wilaya             | Latitude (°N) | Longitude (°E) | Altitude (km) | Tilt $\beta$ (°) | T amb (°C) | $f_{dust}$ | Albedo $\rho$ |
|--------------------|---------------|----------------|---------------|------------------|------------|------------|---------------|
| Adrar              | 27.87         | -0.29          | 0.263         | 29               | 29         | 0.6        | 0.4           |
| Chlef              | 36.17         | 1.34           | 0.066         | 33               | 18         | 0.8        | 0.2           |
| Laghouat           | 33.8          | 2.87           | 0.767         | 33               | 20         | 0.8        | 0.2           |
| Oum El Bouaghi     | 35.87         | 7.11           | 0.9           | 32               | 15         | 0.8        | 0.2           |
| Batna              | 35.55         | 6.17           | 1.05          | 32               | 14         | 0.8        | 0.2           |
| Béjaïa             | 36.75         | 5.08           | 0.034         | 32               | 18         | 0.8        | 0.2           |
| Biskra             | 34.85         | 5.73           | 0.124         | 34               | 22         | 0.8        | 0.2           |
| Béchar             | 31.62         | -2.22          | 0.782         | 33               | 24         | 0.6        | 0.4           |
| Blida              | 36.47         | 2.83           | 0.24          | 30               | 18         | 0.8        | 0.2           |
| Bouira             | 36.38         | 3.9            | 0.975         | 32               | 16         | 0.8        | 0.2           |
| Tamanrasset        | 22.79         | 5.52           | 1.38          | 25               | 26         | 0.6        | 0.4           |
| Tébessa            | 35.4          | 8.12           | 0.82          | 32               | 15         | 0.8        | 0.2           |
| Tlemcen            | 34.88         | -1.32          | 0.428         | 32               | 17         | 0.8        | 0.2           |
| Tiaret             | 35.37         | 1.32           | 1.002         | 32               | 16         | 0.8        | 0.2           |
| Tizi Ouzou         | 36.72         | 4.05           | 0.26          | 32               | 17         | 0.8        | 0.2           |
| Alger              | 36.74         | 3.06           | 0.023         | 32               | 18         | 0.8        | 0.2           |
| Djelfa             | 34.67         | 3.26           | 1.144         | 33               | 16         | 0.8        | 0.2           |
| Jijel              | 36.82         | 5.77           | 0.036         | 32               | 18         | 0.8        | 0.2           |
| Sétif              | 36.19         | 5.41           | 1.096         | 33               | 14         | 0.8        | 0.2           |
| Saïda              | 34.84         | 0.15           | 0.83          | 32               | 17         | 0.8        | 0.2           |
| Skikda             | 36.88         | 6.9            | 0.021         | 31               | 18         | 0.8        | 0.2           |
| Sidi Bel Abbès     | 35.19         | -0.63          | 0.467         | 33               | 18         | 0.8        | 0.2           |
| Annaba             | 36.9          | 7.76           | 0.008         | 31               | 18         | 0.8        | 0.2           |
| Guelma             | 36.46         | 7.43           | 0.446         | 31               | 17         | 0.8        | 0.2           |
| Constantine        | 36.37         | 6.61           | 0.694         | 30               | 15         | 0.8        | 0.2           |
| Médéa              | 36.27         | 2.75           | 0.92          | 32               | 16         | 0.8        | 0.2           |
| Mostaganem         | 35.93         | 0.09           | 0.027         | 33               | 18         | 0.8        | 0.2           |
| M'Sila             | 35.7          | 4.54           | 0.442         | 34               | 18         | 0.8        | 0.2           |
| Mascara            | 35.4          | 0.14           | 0.57          | 33               | 17         | 0.8        | 0.2           |
| Ouargla            | 31.95         | 5.32           | 0.142         | 31               | 26         | 0.6        | 0.4           |
| Oran               | 35.7          | -0.63          | 0.1           | 33               | 18         | 0.8        | 0.2           |
| El Bayadh          | 33.68         | 1.02           | 1.002         | 32               | 17         | 0.8        | 0.2           |
| Illizi             | 26.49         | 8.48           | 0.562         | 28               | 28         | 0.6        | 0.2           |
| Bordj Bou Arréridj | 36.07         | 4.76           | 0.9           | 33               | 16         | 0.8        | 0.2           |
| Boumerdès          | 36.76         | 3.48           | 0.057         | 32               | 18         | 0.8        | 0.2           |
| El Tarf            | 36.77         | 8.31           | 0.02          | 31               | 18         | 0.8        | 0.2           |
| Tindouf            | 27.67         | -8.15          | 0.449         | 28               | 28         | 0.8        | 0.2           |
| Tissemsilt         | 35.6          | 1.81           | 1             | 33               | 16         | 0.8        | 0.2           |
| El Oued            | 33.36         | 6.86           | 0.062         | 33               | 24         | 0.6        | 0.2           |
| Khenchela          | 35.42         | 7.14           | 1.05          | 32               | 14         | 0.8        | 0.2           |
| Souk Ahras         | 36.28         | 7.95           | 0.65          | 31               | 16         | 0.8        | 0.2           |
| Tipaza             | 36.59         | 2.45           | 0.1           | 33               | 18         | 0.8        | 0.2           |
| Mila               | 36.45         | 6.26           | 0.705         | 32               | 16         | 0.8        | 0.2           |
| Aïn Defla          | 36.26         | 1.97           | 0.34          | 31               | 18         | 0.8        | 0.2           |
| Naâma              | 33.27         | -0.31          | 0.9           | 33               | 19         | 0.8        | 0.2           |
| Aïn Témouchent     | 35.3          | -1.14          | 0.245         | 33               | 17         | 0.8        | 0.2           |
| Ghardaïa           | 32.49         | 3.67           | 0.469         | 33               | 23         | 0.6        | 0.4           |
| Relizane           | 35.74         | 0.56           | 0.09          | 33               | 18         | 0.8        | 0.2           |
| Timimoun           | 29.26         | 0.24           | 0.062         | 30               | 24         | 0.6        | 0.4           |
| Bordj Baji Mokhtar | 21.33         | 0.95           | 0.450         | 25               | 27         | 0.6        | 0.4           |
| Ouled Djellal      | 34.42         | 5.07           | 0.120         | 34               | 22         | 0.6        | 0.4           |
| Béni Abbès         | 30.08         | -2.17          | 0.4           | 32               | 30         | 0.6        | 0.4           |
| In Salah           | 27.2          | 2.47           | 0.5           | 29               | 26         | 0.6        | 0.4           |
| In Guezzam         | 19.57         | 5.77           | 0.290         | 22               | 28         | 0.6        | 0.4           |
| Touggourt          | 33.1          | 6.07           | 0.087         | 33               | 24         | 0.6        | 0.4           |
| Djanet             | 24.55         | 9.48           | 0.9           | 25               | 29         | 0.6        | 0.4           |
| El M'Ghair         | 33.95         | 5.92           | 0.259         | 33               | 28         | 0.6        | 0.4           |
| El Meniaa          | 30.58         | 2.88           | 0.4           | 31               | 32         | 0.6        | 0.4           |

# TECHNICAL SPECIFICATIONS – SIMULATION PLATFORM



## PERFORMANCE FEATURES

| ASPECT                  | IMPLEMENTATION                                             |
|-------------------------|------------------------------------------------------------|
| Vectorised calculations | Numpy arrays for 365 days × 58 wilayas (annual production) |
| Real-time simulation    | 0.1s time step → updates every 300ms                       |
| 60fps animation         | Client-side JavaScript (requestAnimationFrame)             |
| Caching                 | GADM GeoJSON cached locally to avoid repeated downloads    |
| Memory efficiency       | Sliding window for history (30 days, ~14 400 entries)      |

## VIEW

Figure B.1 : Technical specification

## Appendix C

$$CO_{2,avoided} = 1.8 * Q_{NH_3}$$

### Wilaya's results – Situation 1 :

The table below presents the wilaya's results in Situation 1

Table C.1 : Full results for all 58 wilayas – Situation 1

| Wilaya         | Ammonia Production<br>(t/an) | Water supply<br>(m³/an) | CO <sub>2</sub> avoided<br>(t/an) | LCOA<br>(€/kg ) | LCOA<br>(DA/kg ) |
|----------------|------------------------------|-------------------------|-----------------------------------|-----------------|------------------|
| Djelfa         | 220.5                        | 588.1                   | 397                               | 1.709           | 247.8            |
| Sétif          | 220                          | 586.6                   | 395.9                             | 1.7135          | 248.5            |
| Khenchela      | 220                          | 586.6                   | 396                               | 1.7133          | 248.4            |
| Batna          | 219.8                        | 586.3                   | 395.7                             | 1.7143          | 248.6            |
| El Bayadh      | 218.4                        | 582.3                   | 393                               | 1.7261          | 250.3            |
| Tiaret         | 217.6                        | 580.2                   | 391.6                             | 1.7323          | 251.2            |
| Tissemsilt     | 217.3                        | 579.5                   | 391.1                             | 1.7345          | 251.5            |
| Oum El Bouaghi | 216.1                        | 576.3                   | 389                               | 1.744           | 252.9            |
| Bouira         | 216                          | 576.1                   | 388.9                             | 1.7446          | 253              |
| Médéa          | 215.2                        | 573.9                   | 387.3                             | 1.7514          | 254              |
| Naâma          | 215.2                        | 573.9                   | 387.4                             | 1.7513          | 253.9            |
| Tébessa        | 215.1                        | 573.8                   | 387.3                             | 1.7518          | 254              |
| Bordj BBA      | 215.1                        | 573.6                   | 387.1                             | 1.7524          | 254.1            |
| Saïda          | 214.3                        | 571.4                   | 385.7                             | 1.759           | 255.1            |
| Laghouat       | 211.6                        | 564.2                   | 380.8                             | 1.7815          | 258.3            |
| Constantine    | 211.5                        | 564.1                   | 380.7                             | 1.7818          | 258.4            |
| Mila           | 211                          | 562.7                   | 379.8                             | 1.7863          | 259              |
| Béchar         | 210.2                        | 560.7                   | 378.4                             | 1.7928          | 260              |
| Souk Ahras     | 210.1                        | 560.2                   | 378.1                             | 1.7943          | 260.2            |
| Mascara        | 208.6                        | 556.4                   | 375.5                             | 1.8064          | 261.9            |
| Tlemcen        | 206.2                        | 550                     | 371.2                             | 1.8276          | 265              |
| Sidi Bel Abbès | 205.9                        | 549.1                   | 370.6                             | 1.8305          | 265.4            |
| Guelma         | 204.8                        | 546.2                   | 368.6                             | 1.8404          | 266.9            |
| M'Sila         | 204.7                        | 546.1                   | 368.5                             | 1.8408          | 266.9            |
| Aïn Defla      | 201.9                        | 538.5                   | 363.4                             | 1.8668          | 270.7            |
| Aïn Témouchent | 201.6                        | 537.7                   | 362.9                             | 1.8696          | 271.1            |
| Tizi Ouzou     | 200.3                        | 534.2                   | 360.5                             | 1.8816          | 272.8            |
| Timimoun       | 199.7                        | 532.7                   | 359.5                             | 1.887           | 273.6            |
| Blida          | 199.3                        | 531.4                   | 358.7                             | 1.8915          | 274.3            |
| Oran           | 196.9                        | 525.1                   | 354.4                             | 1.9144          | 277.6            |
| Relizane       | 196.6                        | 524.3                   | 353.8                             | 1.9172          | 278              |
| Tipaza         | 195.8                        | 522.3                   | 352.5                             | 1.9248          | 279.1            |
| Chlef          | 195.5                        | 521.4                   | 351.9                             | 1.9281          | 279.6            |
| Biskra         | 195.2                        | 520.6                   | 351.3                             | 1.9309          | 280              |
| Mostaganem     | 194.8                        | 519.5                   | 350.6                             | 1.935           | 280.6            |
| Boumerdès      | 194.5                        | 518.9                   | 350.2                             | 1.9373          | 280.9            |
| Béjaïa         | 194                          | 517.4                   | 349.1                             | 1.943           | 281.7            |
| Jijel          | 193.9                        | 517.3                   | 349.1                             | 1.9434          | 281.8            |
| Alger          | 193.7                        | 516.7                   | 348.7                             | 1.9457          | 282.1            |
| El Tarf        | 193.6                        | 516.3                   | 348.4                             | 1.9471          | 282.3            |
| Skikda         | 193.4                        | 516                     | 348.2                             | 1.9483          | 282.5            |
| Annaba         | 193.1                        | 515                     | 347.6                             | 1.9519          | 283              |
| Tamanrasset    | 173.2                        | 462                     | 311.7                             | 2.1761          | 315.5            |
| Djanet         | 165.1                        | 440.5                   | 297.2                             | 2.2826          | 331              |
| Bordj B. M.    | 161.5                        | 430.8                   | 290.6                             | 2.3343          | 338.5            |
| In Salah       | 160.5                        | 428.1                   | 288.9                             | 2.3486          | 340.5            |
| Illizi         | 160.4                        | 427.9                   | 288.7                             | 2.3498          | 340.7            |
| In Guezzam     | 159.1                        | 424.4                   | 286.3                             | 2.3696          | 343.6            |
| Ghardaïa       | 158.9                        | 424                     | 286                               | 2.3719          | 343.9            |
| Tindouf        | 158.1                        | 421.8                   | 284.6                             | 2.3839          | 345.7            |
| Béni Abbès     | 154.6                        | 412.4                   | 278.2                             | 2.4385          | 353.6            |
| Adrar          | 154.3                        | 411.7                   | 277.7                             | 2.4427          | 354.2            |
| El Meniaa      | 152.9                        | 408.1                   | 275.3                             | 2.4642          | 357.3            |
| Ouled Djellal  | 151.8                        | 405.1                   | 273.3                             | 2.4824          | 359.9            |
| Ouargla        | 151.6                        | 404.4                   | 272.8                             | 2.4866          | 360.6            |
| Touggourt      | 151                          | 402.8                   | 271.7                             | 2.4965          | 362              |
| El M'Ghair     | 150.9                        | 402.6                   | 271.6                             | 2.4977          | 362.2            |
| El Oued        | 150.3                        | 401                     | 270.5                             | 2.5078          | 363.6            |

## Wilaya's results – Situation 2 :

The table below presents the wilaya's results in Situation 2

Table C.2 : Full results for all 58 wilayas – Situation 2

| Wilaya         | Ammonia Production<br>(t/an) | Water supply<br>(m³/an) | CO <sub>2</sub> avoided<br>(t/an) | LCOA<br>(€/kg ) | LCOA<br>(DA/kg ) |
|----------------|------------------------------|-------------------------|-----------------------------------|-----------------|------------------|
| Djelfa         | 307.0                        | 818.3                   | 552.6                             | 1.6694          | 242.1            |
| Khenchela      | 306.4                        | 816.9                   | 551.6                             | 1.6725          | 242.5            |
| Batna          | 306.3                        | 816.7                   | 551.4                             | 1.6729          | 242.6            |
| Sétif          | 306.2                        | 816.3                   | 551.2                             | 1.6735          | 242.7            |
| El Bayadh      | 306.1                        | 816.1                   | 551.1                             | 1.674           | 242.7            |
| Tiaret         | 305.4                        | 814.2                   | 549.8                             | 1.6779          | 243.3            |
| Tissemsilt     | 305.1                        | 813.5                   | 549.3                             | 1.6795          | 243.5            |
| Naâma          | 304.7                        | 812.2                   | 548.4                             | 1.6821          | 243.9            |
| Bouira         | 304.5                        | 811.8                   | 548.1                             | 1.683           | 244              |
| Oum El Bouaghi | 304.4                        | 811.6                   | 548                               | 1.6834          | 244.1            |
| Médéa          | 304.0                        | 810.5                   | 547.3                             | 1.6855          | 244.4            |
| Tébessa        | 303.9                        | 810.3                   | 547.1                             | 1.6861          | 244.5            |
| Bordj BBA      | 303.9                        | 810.1                   | 547                               | 1.6864          | 244.5            |
| Saïda          | 303.8                        | 809.9                   | 546.8                             | 1.6869          | 244.6            |
| Béchar         | 302.8                        | 807.2                   | 545                               | 1.6926          | 245.4            |
| Laghouat       | 302.7                        | 807.0                   | 544.9                             | 1.6929          | 245.5            |
| Constantine    | 302.0                        | 805.2                   | 543.7                             | 1.6967          | 246              |
| Mila           | 301.7                        | 804.2                   | 543                               | 1.6989          | 246.3            |
| Souk Ahras     | 301.2                        | 803.1                   | 542.2                             | 1.7012          | 246.7            |
| Mascara        | 300.4                        | 800.9                   | 540.8                             | 1.7057          | 247.3            |
| Tlemcen        | 299.2                        | 797.6                   | 538.5                             | 1.713           | 248.4            |
| Sidi Bel Abbès | 299.0                        | 797.1                   | 538.2                             | 1.7139          | 248.5            |
| Guelma         | 298.3                        | 795.2                   | 536.9                             | 1.7181          | 249.1            |
| M'Sila         | 298.2                        | 794.9                   | 536.7                             | 1.7186          | 249.2            |
| Aïn Defla      | 296.7                        | 790.9                   | 534                               | 1.7273          | 250.5            |
| Aïn Témouchent | 296.3                        | 789.8                   | 533.3                             | 1.7298          | 250.8            |
| Tizi Ouzou     | 295.4                        | 787.6                   | 531.8                             | 1.7348          | 251.5            |
| Blida          | 295.1                        | 786.8                   | 531.2                             | 1.7365          | 251.8            |
| Oran           | 293.4                        | 782.3                   | 528.2                             | 1.7464          | 253.2            |
| Relizane       | 293.3                        | 781.8                   | 527.9                             | 1.7475          | 253.4            |
| Biskra         | 293.0                        | 781.1                   | 527.4                             | 1.749           | 253.6            |
| Tipaza         | 292.7                        | 780.2                   | 526.8                             | 1.751           | 253.9            |
| Chlef          | 292.5                        | 779.8                   | 526.5                             | 1.7521          | 254              |
| Mostaganem     | 292.1                        | 778.7                   | 525.7                             | 1.7546          | 254.4            |
| Boumerdès      | 291.9                        | 778.2                   | 525.4                             | 1.7557          | 254.6            |
| Béjaïa         | 291.5                        | 777.2                   | 524.8                             | 1.7579          | 254.9            |
| Jijel          | 291.5                        | 777.1                   | 524.7                             | 1.7581          | 254.9            |
| Alger          | 291.4                        | 776.7                   | 524.4                             | 1.759           | 255.1            |
| El Tarf        | 291.3                        | 776.7                   | 524.4                             | 1.7591          | 255.1            |
| Skikda         | 291.2                        | 776.4                   | 524.2                             | 1.7596          | 255.1            |
| Annaba         | 291.0                        | 775.8                   | 523.8                             | 1.7611          | 255.4            |
| Tamanrasset    | 288.2                        | 768.2                   | 518.7                             | 1.7784          | 257.9            |
| Djanet         | 281.6                        | 750.7                   | 506.9                             | 1.82            | 263.9            |
| Bordj B. M.    | 278.0                        | 741.3                   | 500.5                             | 1.8432          | 267.3            |
| Illizi         | 276.8                        | 738.0                   | 498.2                             | 1.8515          | 268.5            |
| In Salah       | 276.5                        | 737.1                   | 497.6                             | 1.8537          | 268.8            |
| In Guezzam     | 276.1                        | 736.2                   | 497                               | 1.856           | 269.1            |
| Ghardaïa       | 273.9                        | 730.3                   | 493                               | 1.871           | 271.3            |
| Tindouf        | 273.4                        | 728.8                   | 492.1                             | 1.8746          | 271.8            |
| Béni Abbès     | 271.0                        | 722.6                   | 487.9                             | 1.8909          | 274.2            |
| Adrar          | 270.9                        | 722.3                   | 487.7                             | 1.8916          | 274.3            |
| El Meniaa      | 269.7                        | 719.0                   | 485.4                             | 1.9003          | 275.5            |
| Timimoun       | 269.0                        | 717.2                   | 484.2                             | 1.9052          | 276.3            |
| Ouargla        | 267.3                        | 712.6                   | 481.1                             | 1.9175          | 278              |
| Ouled Djellal  | 266.6                        | 710.8                   | 479.9                             | 1.9223          | 278.7            |
| El M'Ghair     | 266.5                        | 710.6                   | 479.8                             | 1.9228          | 278.8            |
| Touggourt      | 266.2                        | 709.7                   | 479.2                             | 1.9252          | 279.2            |
| El Oued        | 263.7                        | 703.2                   | 474.7                             | 1.9431          | 281.7            |