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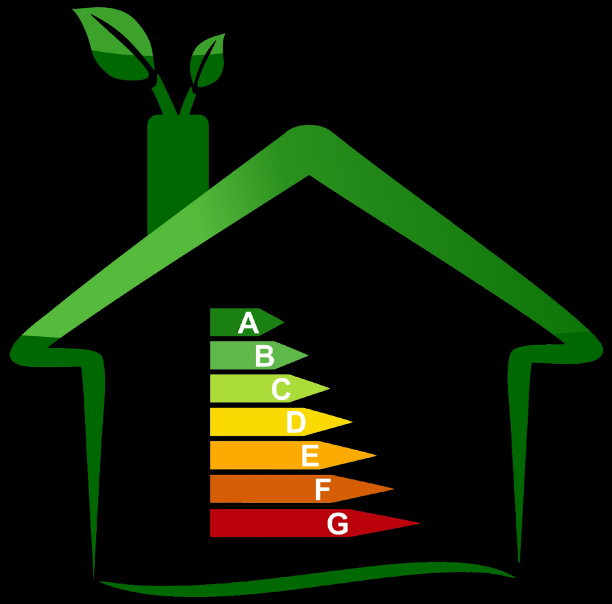
政策研究大学院大学
NATIONAL GRADUATE INSTITUTE FOR POLICY STUDIES

Assessing Hydrogen Economy Development in Egypt: Evaluation of Sustainable Hydrogen Production Technologies Using FAHP Analysis

Ibrahim Kshanh, Egypt

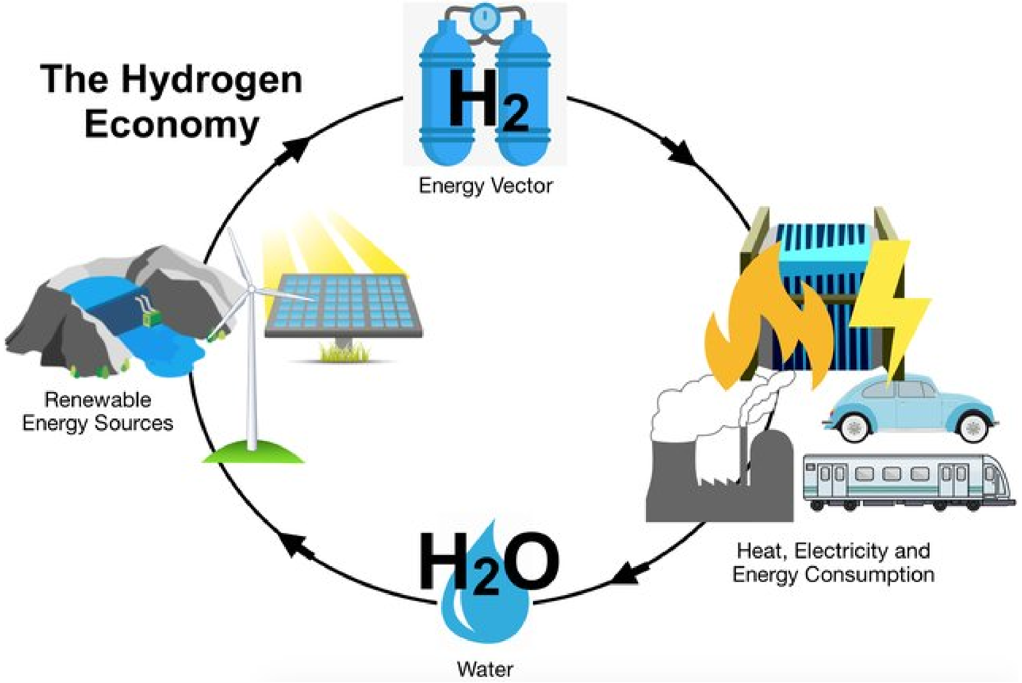
Background



Energy sector analysis, Egypt's energy strategy, hydrogen potential

Hydrogen economy definition

The hydrogen economy is a hypothetical future economy in which **hydrogen is used as a clean energy carrier** that can provide a more sustainable and efficient means of meeting energy needs than the fossil fuel-based economy on which we currently rely. However, there are obstacles to the widespread adoption of a hydrogen economy, including **high production costs, limited infrastructure and production capability** (Yue et al., 2021)

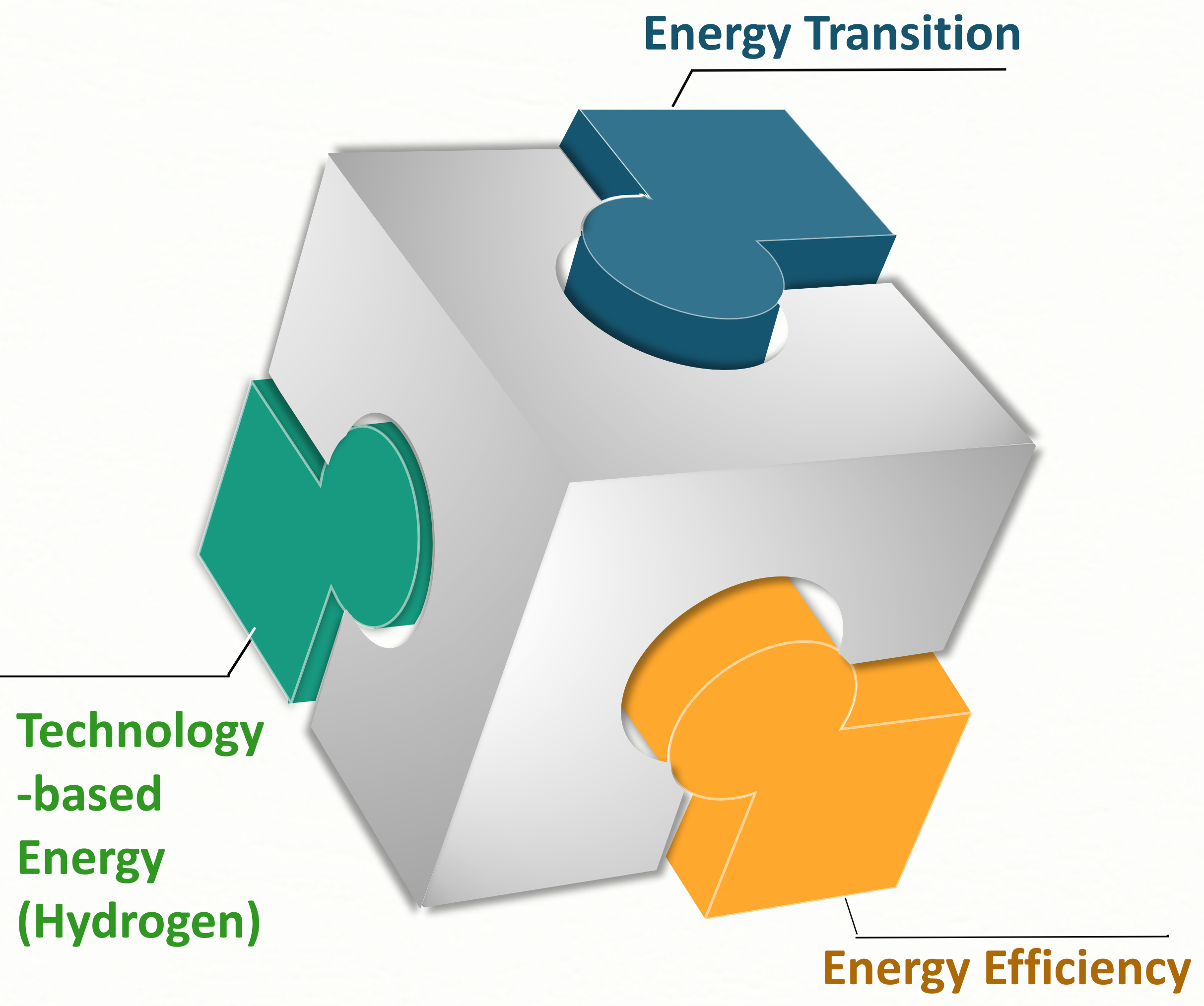


Background

Sustainable Development Scenario, and Net-zero emission plans

- Accelerating energy transition to renewables and clean energy as solar and wind are essential
- Hydrogen, CCUS and gasification
- Increasing Energy-efficiency for the existing infrastructure

Electrification cannot decarbonize entire economies alone, additional hydrogen generation is needed. This hydrogen forms a bridge between the power sector and industries where the direct use of electricity would be challenging, such as in the production of steel from iron ore or fuelling large ships.



IEA, Energy Technology Perspectives (2020)

Background

110 Million Population

1 Non-OPEC Oil Producer in Africa

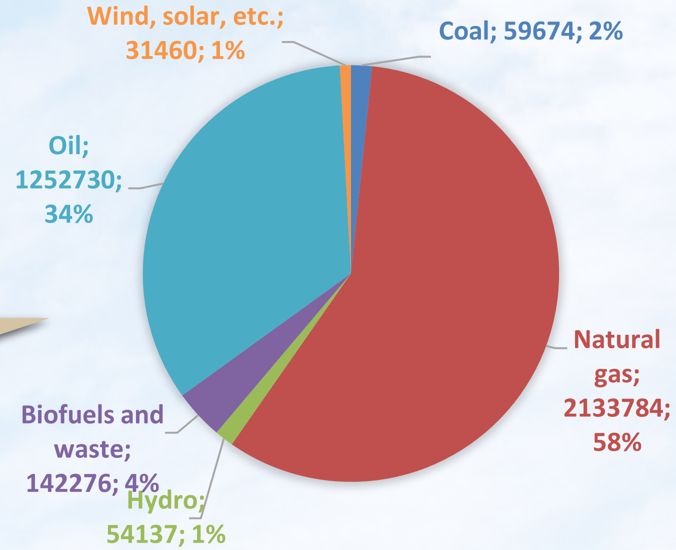
2 Gas Producer in Africa

13 In Global Gas Production

16 Worldwide in Gas Reserves ~ 1% of global reserves

22 Worldwide in Electricity Production

رؤية 2030 VISION OF EGYPT



consumption

OIL 25

NG 18

INDC

- Efficient End-users
- Advanced E-tech
- Increase RE
- Policy Enforcement
- Reform E-Subsidies

Source; MOEE, 2015

Sustainable Development Strategy

Egypt Vision 2030 Energy Pillar

1. Ensuring energy security
2. Increasing energy sector's contribution to the GDP
3. Maximizing utilization of local energy resources

2030
VISION OF EGYPT

4. Promoting the sector's rational and sustainable management
5. Reducing energy intensity
6. Reducing emissions from the energy sector

Hydrogen contributes to achieving Egypt's energy goals

Hydrogen potential in Egypt (Blue &Green)

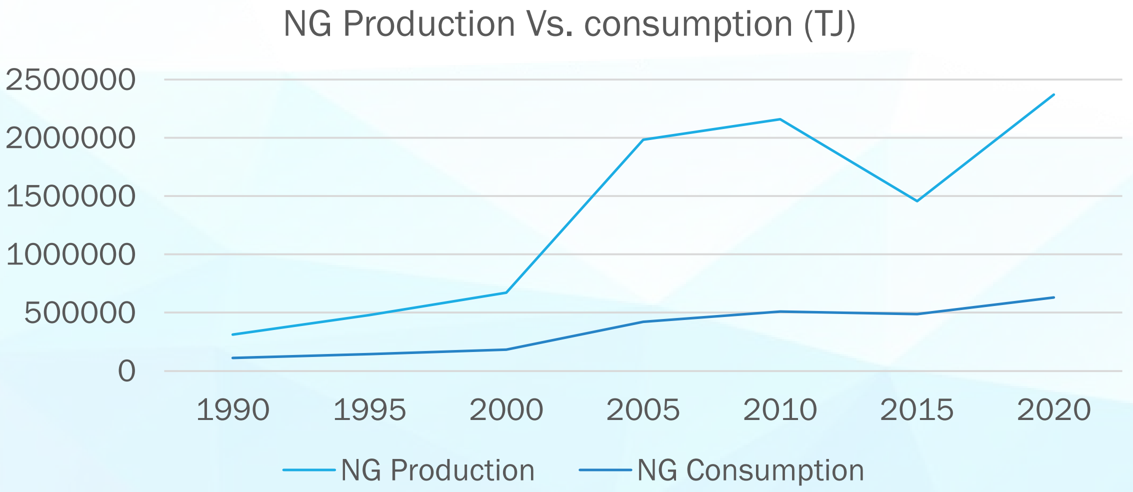
Egypt's Energy Strategy; Transition Towards Clean Fuels

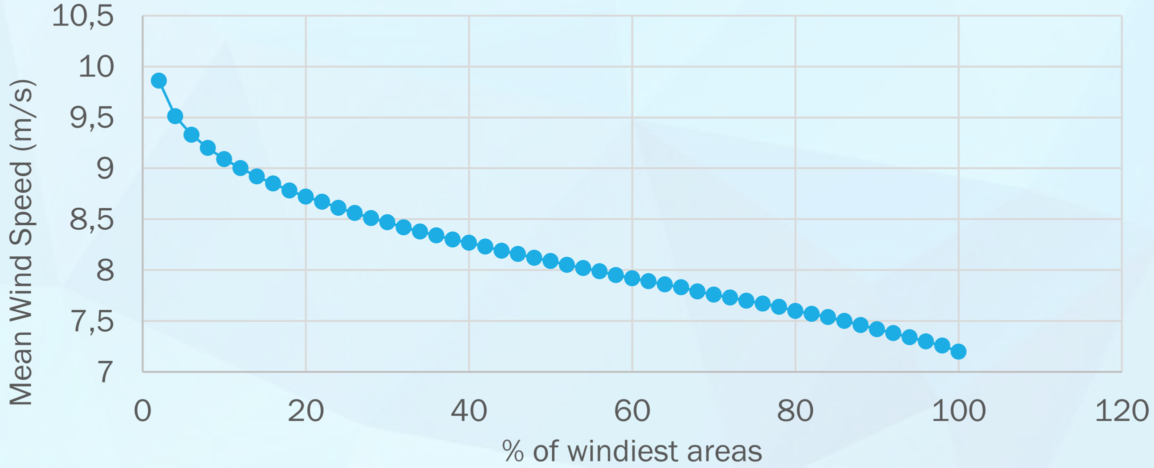
- ☐ Progressive increase in volumes of natural gas production
- ☐ Boost the share of renewable energy generation

Renewable energy generation share exceeding the planned targets

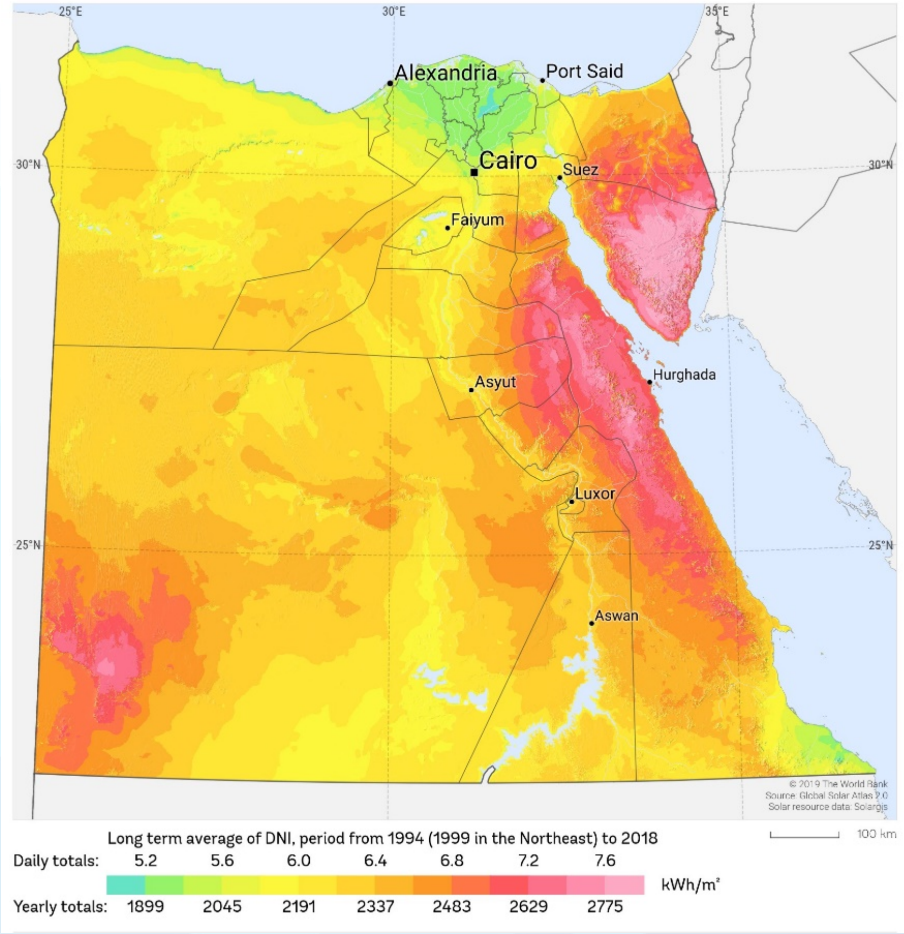
37 %	→	42 %	→	60 %
Approved scenario in 2016		Update in 2017		Update in 2019 for 2040

Natural Gas and renewables availability





Consistent and robust wind speeds,
which average between eight and 10 m/s at an altitude 100 meters

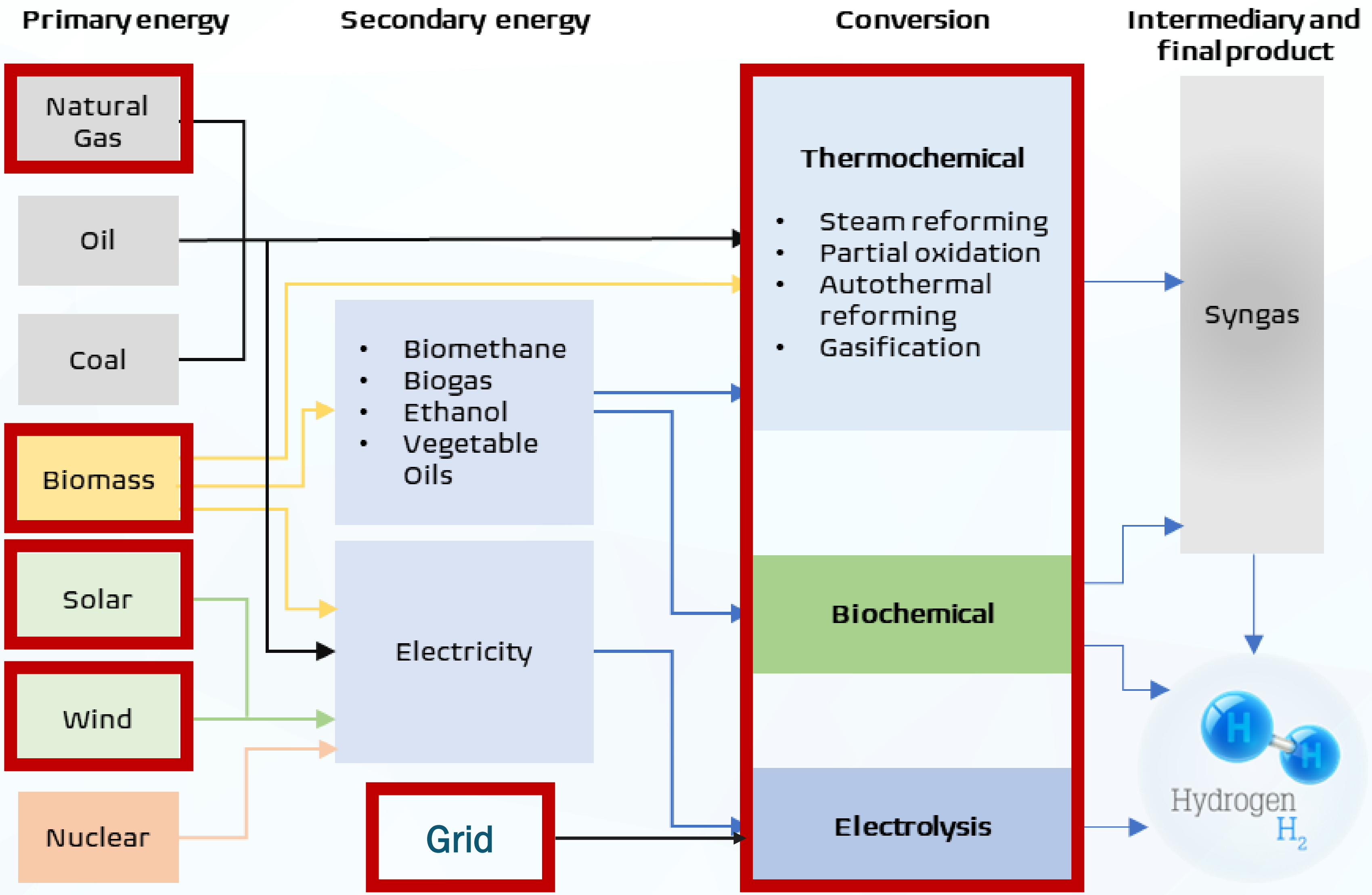


Direct solar radiation ranging from 2000 to 3200 kWh/m2/y,

Under development Hydrogen projects

No.	Date	Agreement	Application	Foreign entity	Egyptian entity	Capacity
1	Mar. 2021	Feasibility study of producing low-carbon fuel in Egypt	Hydrogen production and export for marine applications	Belgium's Dredging, Environmental, and Marine Engineering Group (DEME)	Ministry of Electricity and Renewable Energy (MoERE), Ministry of petroleum and mineral resources (MoPMR), and The Egyptian Navy	Undefined
2	Aug. 2021	MOU agreement/ pilot project	Green hydrogen	Siemens	MoERE, MoPMR, and the Egyptian navy	100 – 200 MW
3	Jul. 2021	Technical and commercial feasibility study	Green Hydrogen and blue hydrogen with CCS	Eni	Egyptian natural gas holding company (EGAS)	Undefined
4	Nov. 2021	Project development	Ammonia with CCSU	Fertiglobe Partners with Scatec	The Sovereign Fund of Egypt (SFE)	90,000 tons/year
5	Mar. 2022	MOU towards the construction of a large-scale production facility	Green hydrogen to be used as a fuel for ships	Maersk (Maritime transportation)	The General Authority for Suez Canal (GASC), NREA, MoERE	Undefined
6	Mar. 2022	MOU agreement	Green ammonia	Scatec	SFE, GASC, NREA, and EETC	one million tons/yer
7	Mar. 2022	Project development	Green ammonia	Petrofac	Mediterranean Energy Partners	125,000 tons/year
8	Mar. 2022	MOU and feasibility study	Green hydrogen and ammonia	Total	Abu Qir Fertilizers	Undefined
9	Apr. 2022	MOU and feasibility study	Green hydrogen and ammonia	AMEA Power of the United Arab Emirates	GASC, SFE, NREA, and EETC	390,00 tons/year
10	Apr. 2022	MOU and feasibility study	Green ammonia	France's EDF Renewables	GASC, SFE, NREA, and EETC	350 tons/year
11	Apr. 2022	Project development	Green ammonia	Masdar	Hassan Allam (HA) Utilities	480,000 tons/year
12	Nov. 2022	MOU and feasibility study	Green hydrogen	Fortescue Future Industries (FFI)	NREA and EETC	9.2 GW
13	Nov. 2022	framework agreement	Green hydrogen	ReNew Power, India	Government of Egypt and Elsewedy Group	20,000 tons/year

Hydrogen Production Technologies

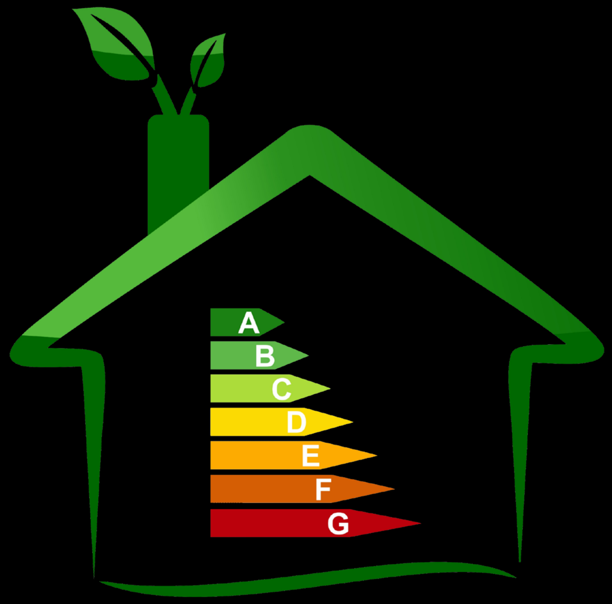


Proposed Technologies

- ✓ Natural-gas reforming (SMR)
- ✓ Biomass gasification (BG)
- ✓ PV Electrolysis (PVE)
- ✓ Wind Electrolysis (WE)
- ✓ Grid Electrolysis (GE)

(Ericsson, 2017; IEA, 2019).

Proposed Research



Literature, Gap, Questions, methods

Aim of the study

This study aims to develop an MCDM-based model that incorporates uncertainties in evaluating the sustainability of HPTs, a case study of Egypt. The model proposed here utilizes **FAHP methodology** to establish a sustainability criteria hierarchy, assigning weights to each criterion. Furthermore, the FAHP method will be employed here to rank HPT alternatives, thus enabling the identification of the most sustainable options. The overall aims of this study could be summarized as follows:

I. Illustrate and analyze the essential components of the energy sector in Egypt, particularly energy sources, including renewable energy. The primary objective is to assess Egypt's potential for hydrogen production.

II. Identify the HPTs that are most suitable for commercial development in Egypt.

III. Define the main sustainability criteria and sub-criteria for the evaluation of HPT; then construct a hierarchy structure for the evaluation process.

IV. Utilize the FAHP to prioritize HPT, to assist Egyptian decision-makers to develop a national hydrogen economy strategy, that could contribute to the effectiveness of implementations of Egypt's sustainable development strategy.

V. Identify the opportunities and challenges of Egypt's hydrogen economy development

Research Gap

- Limited scientific research, especially economic and environmental assessment of the hydrogen economy at the national level, with a focus on developing countries (so far, null about Egypt)

- There are knowledge gaps in the MCDM method for HPT prioritization; for example, several research focused on the evaluation of HPT in general, while limited studies focused on evaluating HPT for a particular country or region

- There are still no widely agreed criteria for the evaluation of balanced sustainability (environmental, economic, and social aspects). calculations of relative evaluation criteria weights are usually based on stakeholder preference under uncertainties, especially for studies at the national planning level.

Research questions

1. Based on the available energy sources in Egypt, including renewable energy. what is their potential for hydrogen production?

   Which hydrogen production technologies (HPTs) are considered the most viable and commercially feasible for commercial development in Egypt?

2. What are the main criteria and sub-criteria that should be used to evaluate the sustainability of HPTs in Egypt?

3. How can the FAHP-based model assist Egyptian decision-makers in developing a hydrogen economy strategy that aligns with the country's sustainable development goals?

   How can the identification of sustainable hydrogen production options in Egypt contribute to global efforts in transitioning to a low-carbon economy?

Methodology

Fuzzy Analytic Hierarchy Process (FAHP)

AHP and FAHP

Analytic Hierarchy Process (AHP)

- MCDM method
- Originally developed by **Prof. Thomas L. Saaty** at the end of 70's
- Applied to many practical decision-making problems

Complex Decision Problem

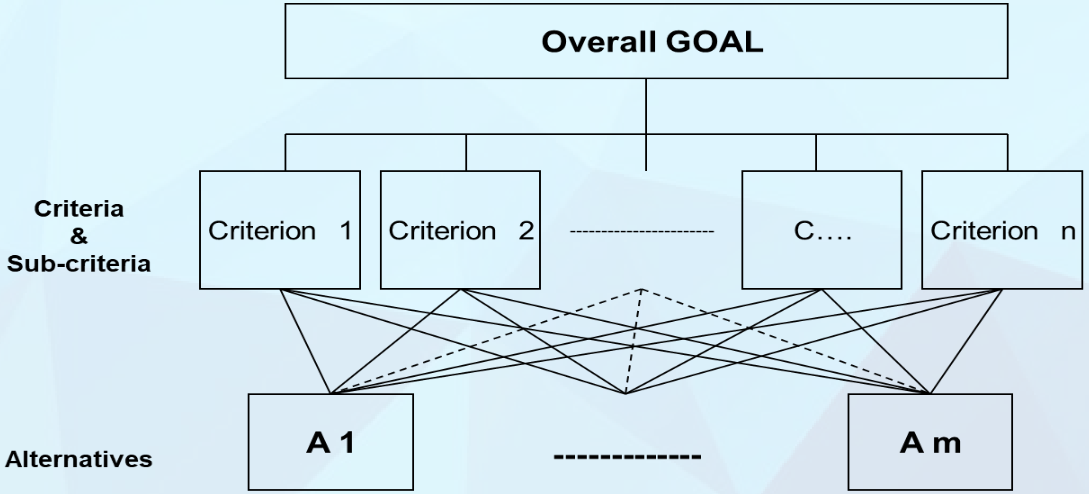
Multiple Criteria (Qualitative & Quantitative)

Multiple Decision Makers

Uncertainty

- Incomplete Information
- Imprecise Data
- Vagueness surrounding the decision making

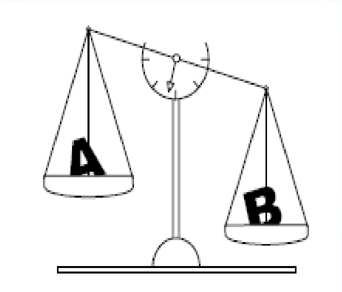
AHP Problem Structuring



AHP and FAHP

Pair-wise Comparison Method

- Pair-wise comparisons in the AHP assume that DM can :



I. compare any two elements at the same level of the hierarchy $E_i \, , E_j$

II. provide a numerical value for the ratio of their importance a_{ij}

The ***9-point scale*** of Saaty

E1	9	7	5	3	1	3	5	7	9	E2

This means E2 has strong Importance relative to E1

9-point Scale

- 1 = Equal Importance
- 3 = Moderate Importance
- 5 = Strong Importance
- 7 = Very Strong Importance
- 9 = Extreme Importance
- 2,4,6,8 : Intermediate values

$$R = \begin{array}{c} \begin{matrix} A & B & C & \ldots\ldots & .. & X \end{matrix} \\ \begin{bmatrix} 1 & a_{12} & a_{13} & \ldots\ldots & .. & a_{1n} \\ a_{21} & 1 & a_{23} & \ldots\ldots & .. & a_{2n} \\ a_{31} & a_{32} & 1 & \ldots\ldots & .. & a_{3n} \\ .. & .. & .. & .. & .. & .. \\ a_{n1} & a_{n2} & a_{n3} & \ldots\ldots & .. & 1 \end{bmatrix} \end{array}$$

n elements require

n (n − 1) / 2 judgments

$$w = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}$$

were $a_{ji} = 1/a_{ij}$, *i=1,2,…..,n* and *j=1,2,…..,n*

AHP and FAHP

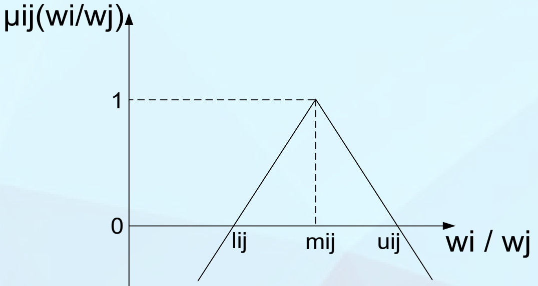
Proposed By Dr. Ludmil Mikhailov in 2002

Linguistic Variables

E1	Extremely Important	Very Strongly Important	Moderately Important	Nearly Equal Important	Moderately Important	Very Strongly Important	Extremely Important	E2

- The most appropriate model that captures the characteristics of the Linguistic variables is ***Fuzzy Numbers*** rather than ***Definite (Crisp) Numbers*** as used by Saaty
- Therefore, the ***Modified Scale*** Replacing the ***9-point scale*** of Saaty could be given as follows:

Linguistic variable	Fuzzy number	Triangular Membership Function
Nearly Equally Preferred	$\tilde{1}$	(1/2 , 1 , 2)
Equally to Moderately Preferred	$\tilde{2}$	(1 , 2 , 3)
Moderately Preferred	$\tilde{3}$	(2 , 3 , 4)
Moderately to Strongly Preferred	$\tilde{4}$	(3 , 4 , 5)
Strongly Preferred	$\tilde{5}$	(4 , 5 , 6)
Strongly to Very Strongly Preferred	$\tilde{6}$	(5 , 6 , 7)
Very Strongly Preferred	$\tilde{7}$	(6 , 7 , 8)
Very Strongly to Extremely Preferred	$\tilde{8}$	(7 , 8 , 9)
Extremely Preferred	$\tilde{9}$	(8 , 9 , 9 1/2)

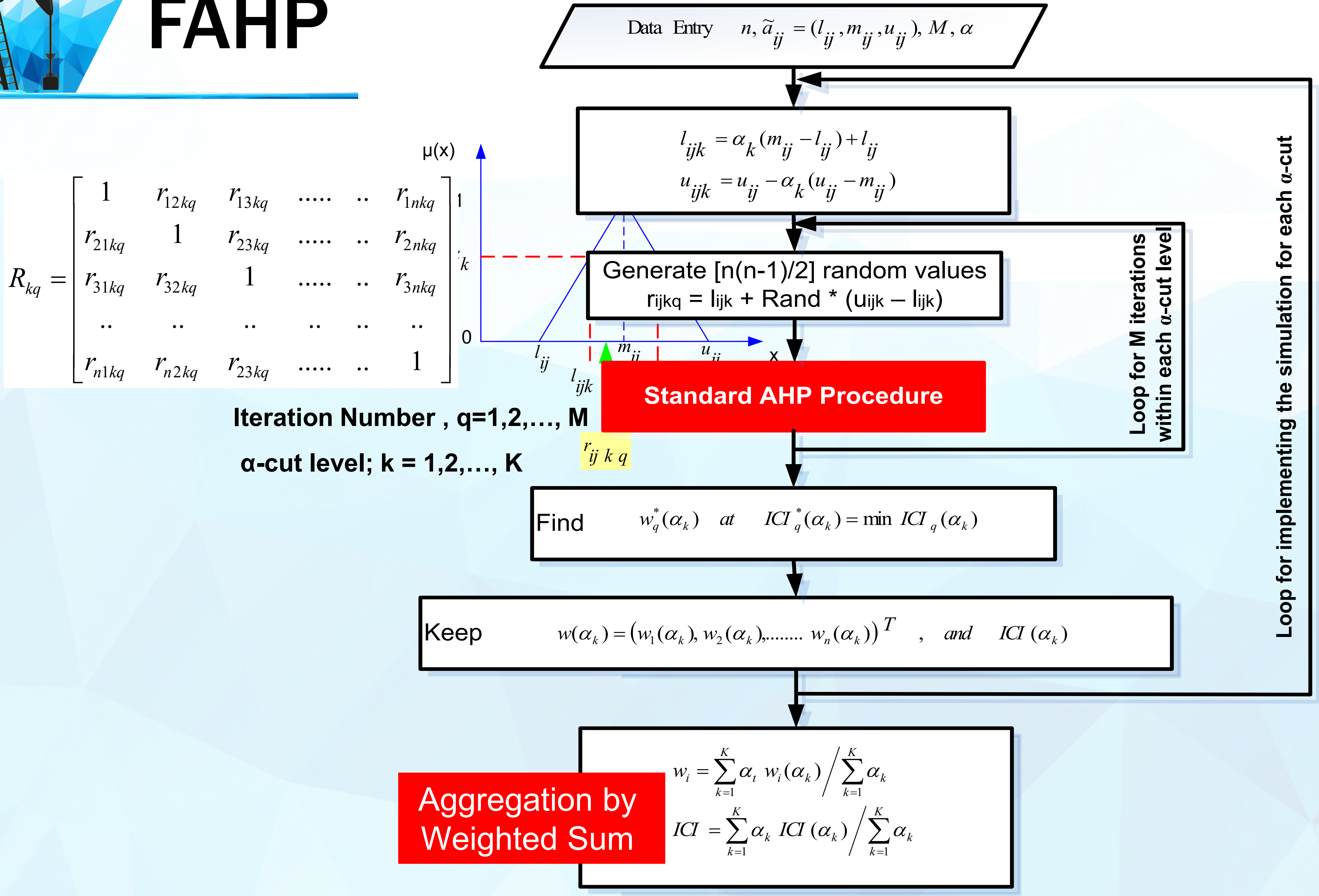


$$\tilde{R} = \begin{array}{c|cccccc} & A & B & C & ..... & .. & X \\ \hline A & 1 & \tilde{a}_{12} & \tilde{a}_{13} & ..... & .. & \tilde{a}_{1n} \\ B & \tilde{a}_{21} & 1 & \tilde{a}_{23} & ..... & .. & \tilde{a}_{2n} \\ C & \tilde{a}_{31} & \tilde{a}_{32} & 1 & ..... & .. & \tilde{a}_{3n} \\ .... & .. & .. & .. & .. & .. & .. \\ X & \tilde{a}_{n1} & \tilde{a}_{n2} & \tilde{a}_{n3} & ..... & .. & 1 \end{array}$$

where :

$$\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij}) \quad and \quad \tilde{a}_{ji} = 1/\tilde{a}_{ij} = (1/u_{ij}, 1/m_{ij}, 1/l_{ij})$$

FAHP



Data Entry $n, \tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij}), M, \alpha$
$l_{ijk} = \alpha_k (m_{ij} - l_{ij}) + l_{ij}$
$u_{ijk} = u_{ij} - \alpha_k (u_{ij} - m_{ij})$
μ(x)
1
0
x
l_{ij}
m_{ij}
u_{ij}
l_{ijk}
$r_{ij\,k\,q}$
$R_{kq} = \begin{bmatrix} 1 & r_{12kq} & r_{13kq} & \cdots\cdots & .. & r_{1nkq} \\ r_{21kq} & 1 & r_{23kq} & \cdots\cdots & .. & r_{2nkq} \\ r_{31kq} & r_{32kq} & 1 & \cdots\cdots & .. & r_{3nkq} \\ .. & .. & .. & .. & .. & .. \\ r_{n1kq} & r_{n2kq} & r_{23kq} & \cdots\cdots & .. & 1 \end{bmatrix}$
Generate [n(n-1)/2] random values
rijkq = lijk + Rand * (uijk – lijk)
Standard AHP Procedure
Iteration Number , q=1,2,…, M
α-cut level; k = 1,2,…, K
Loop for M iterations within each α-cut level
Loop for implementing the simulation for each α-cut
Find $w_q^*(\alpha_k)$ at $ICI_q^*(\alpha_k) = \min ICI_q(\alpha_k)$
Keep $w(\alpha_k) = \left(w_1(\alpha_k), w_2(\alpha_k), \ldots\ldots w_n(\alpha_k)\right)^T$, and $ICI(\alpha_k)$
Aggregation by Weighted Sum
$w_i = \sum_{k=1}^{K} \alpha_t \, w_i(\alpha_k) \Big/ \sum_{k=1}^{K} \alpha_k$
$ICI = \sum_{k=1}^{K} \alpha_k \, ICI(\alpha_k) \Big/ \sum_{k=1}^{K} \alpha_k$

AHP Vs. FAHP

The AHP uses the 9-point scale to implement the pair-wise comparisons.

- ✓ This numerical scale leads to having the human judgments represented as exact numbers.
- ✓ However, in practical cases the human preference model is uncertain, and decision-makers may be unable to assign exact numerical values to the comparison judgments.

It is very useful to use linguistic variables which are more familiar to the decision maker instead of the numerical scale of AHP

A good approach to applying the linguistic variables is using the fuzzy set theory within the AHP framework leading to what we call FAHP or Fuzzy Analytic Hierarchy process

Application of FAHP

Evaluation of Hydrogen Production Technology in Egypt

Study Framework (Fuzzy Analytic Hierarchy Process)

Step 1; Main goal
Evaluation of HPT considering sustainability

Step 2; determine prioritization criteria and sub-criteria

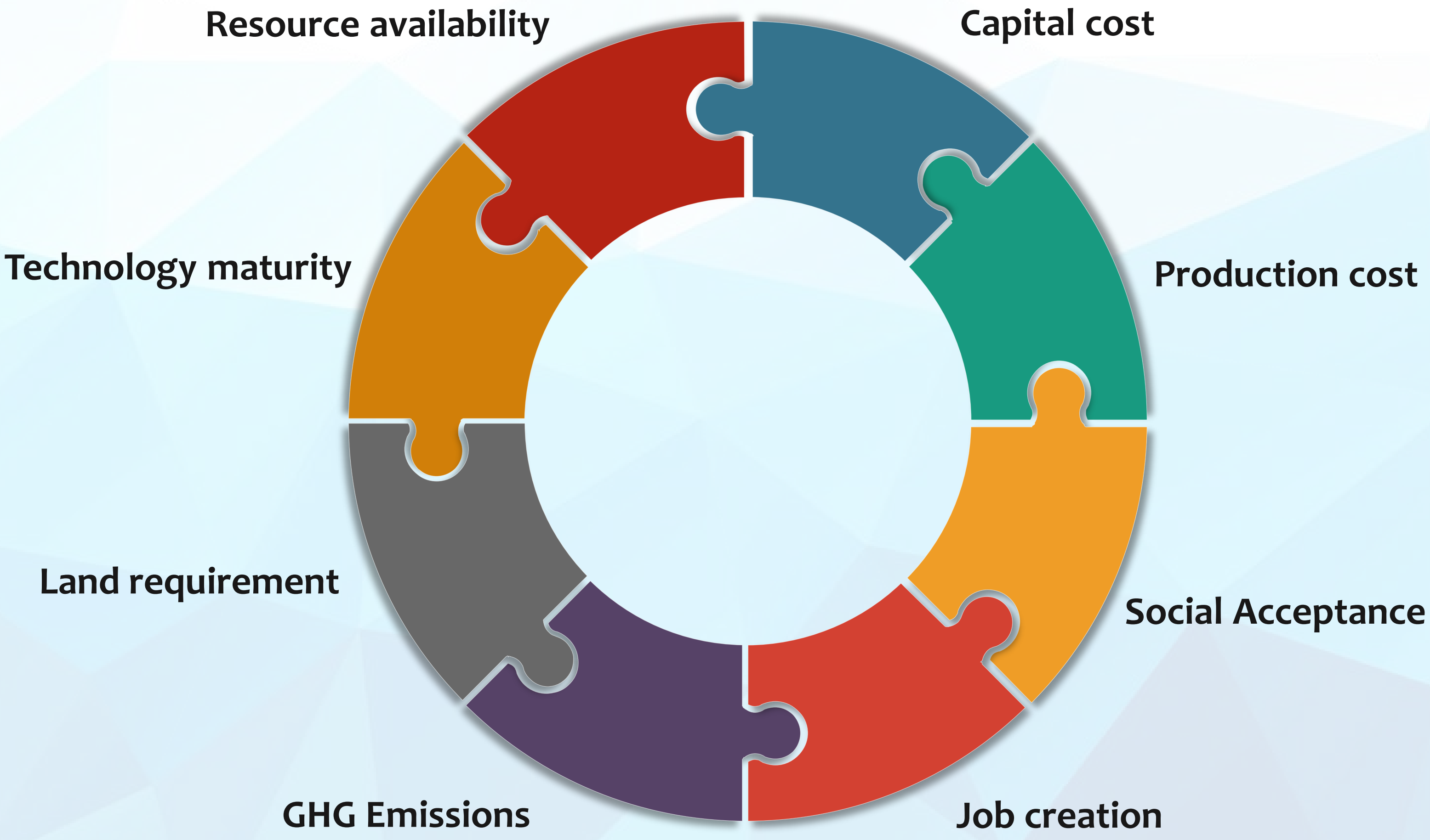
Step 3; Hierarchical Structure Construction
Present the structure of the criteria, Sub-criteria, and alternatives

Step 4; Select the Decision-Making expert
Technical Expert working in governmental energy institutions or private sector

Step 5; Individual Judgment for FAHP Model
Using fuzzy pairwise comparison method

Step 6: Aggregation of Individual Analysis Results
Score calculations

Step 2; Determine Prioritization Criteria

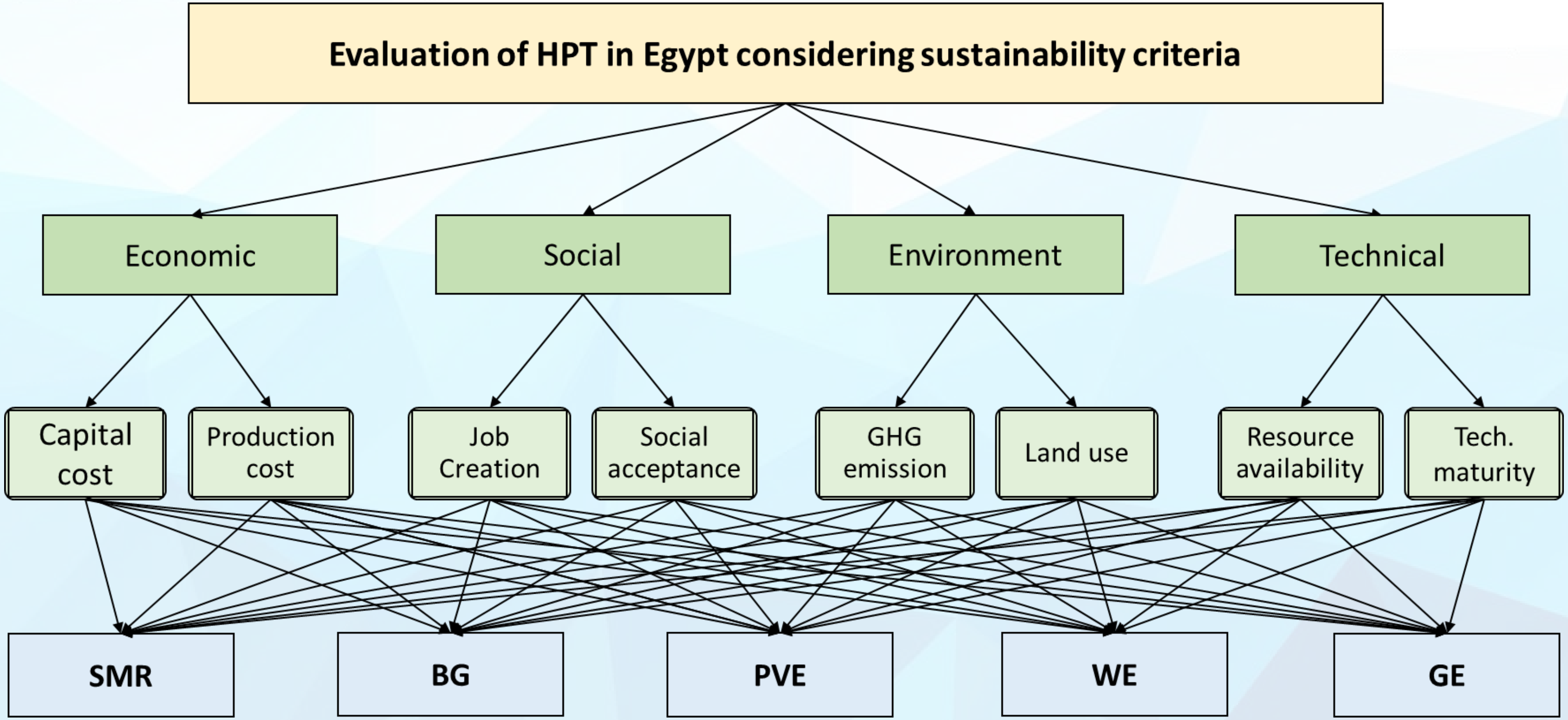


Step 3; FAHP Hierarchy Structure

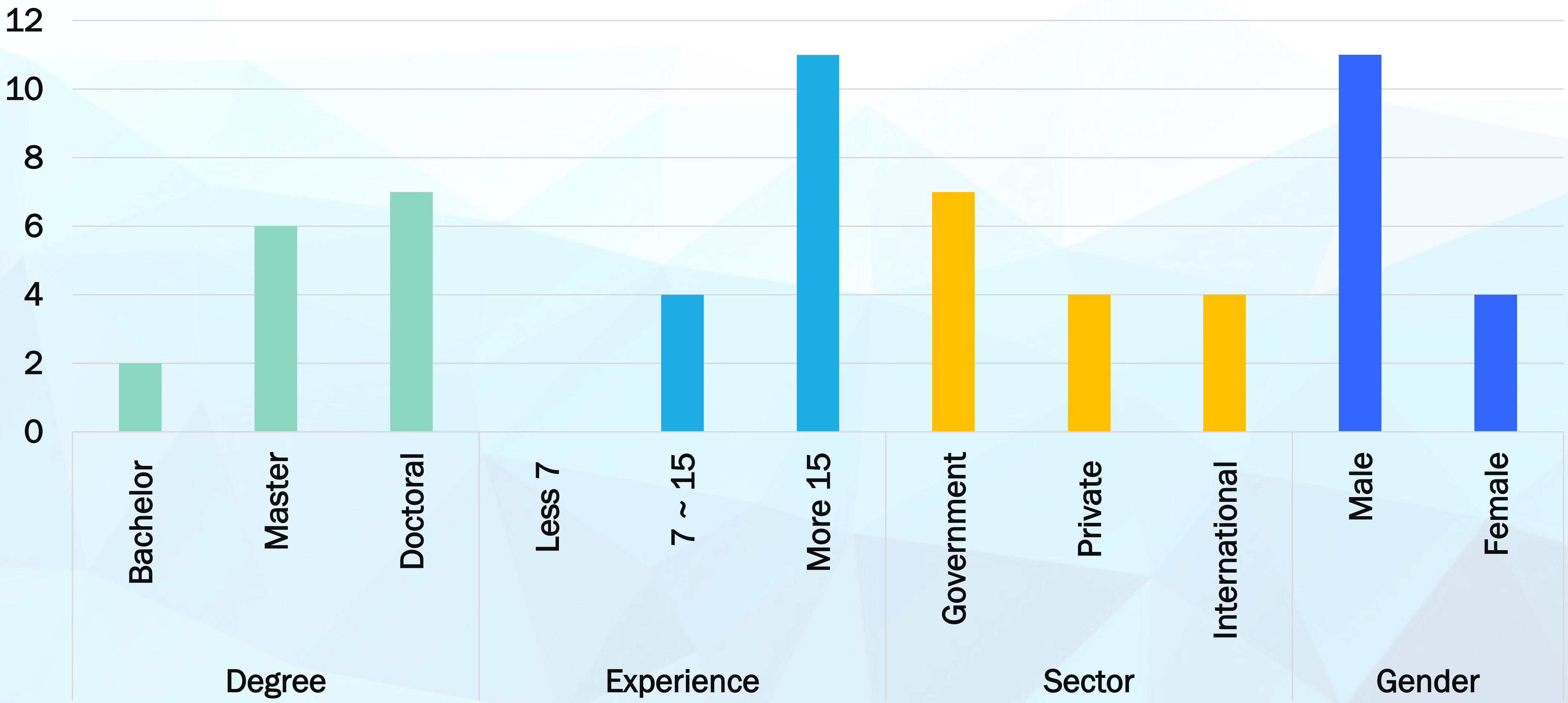
1 Goal

2 Identify criteria and sub-criteria

3 Alternatives



Step 4; Selection of DM expert



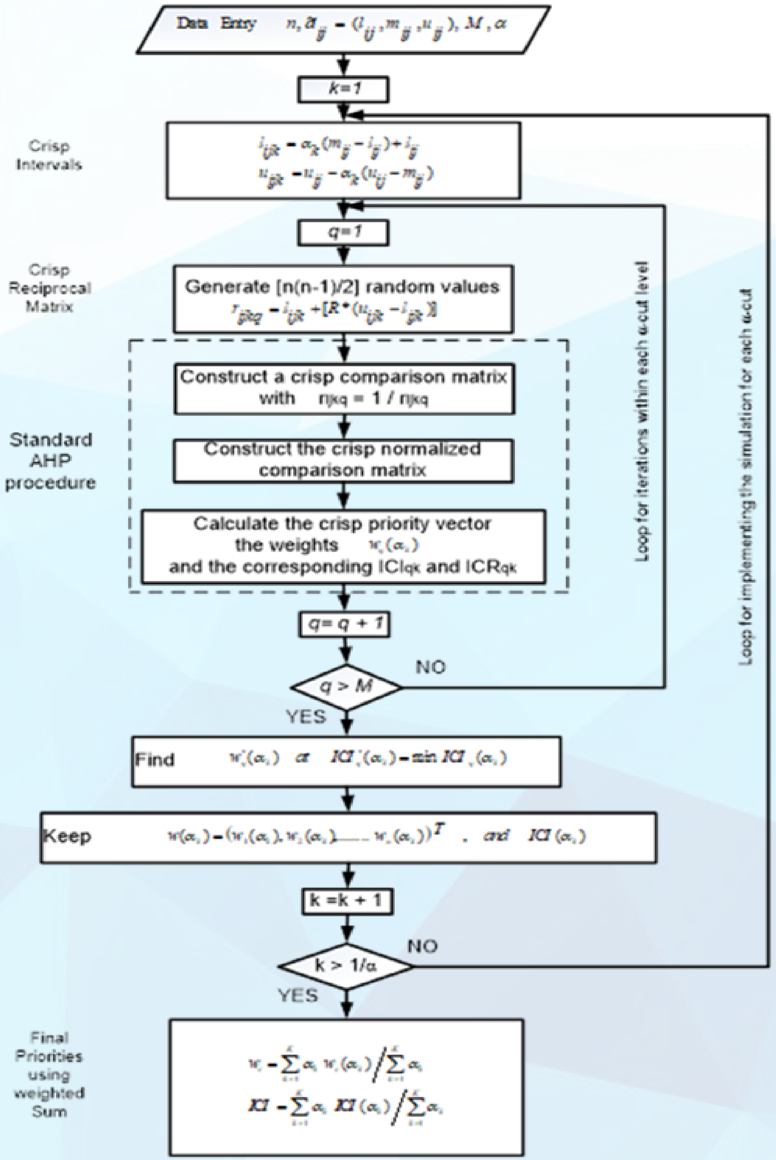
Total of 15 Egyptian Expert

Step 5; Individual Judgment for FAHP Model

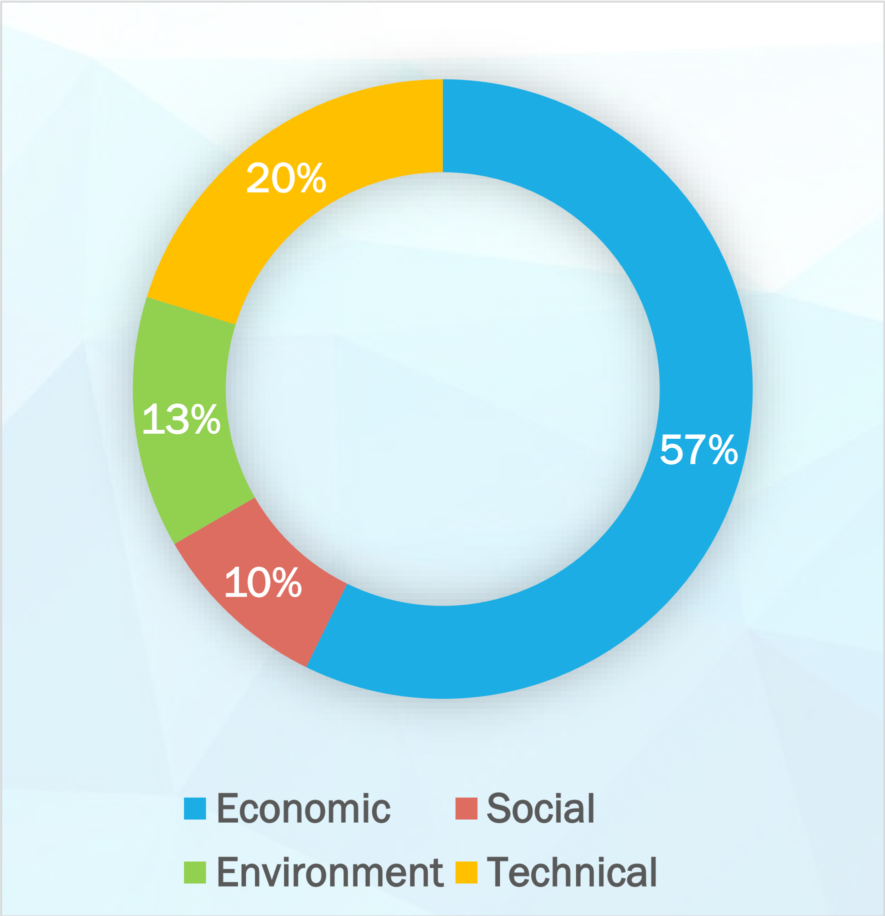
1) Pairwise comparison between main criteria concerning goal

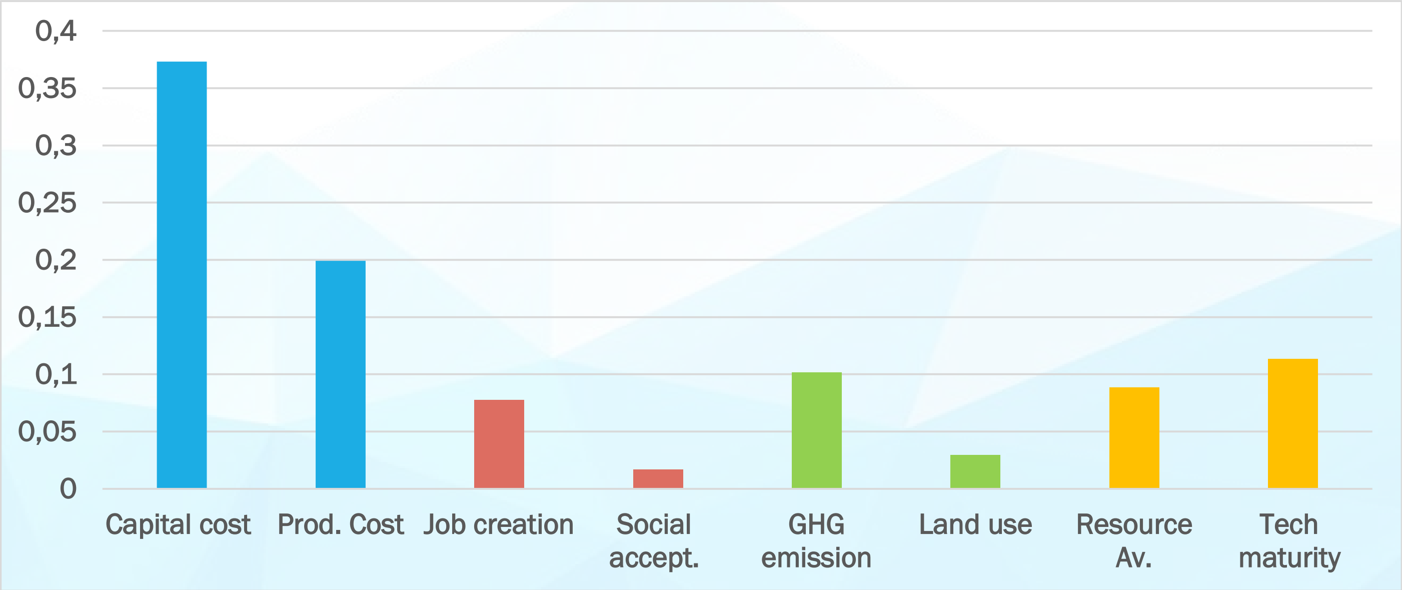
Main Criteria	Preference Degree																	Main Criteria
	Extreme	very strong to extreme	Very Strong	strong to very strong	Strong	Moderate to strong	Moderate	equal to moderate	Equal	equal to moderate	Moderate	Moderate to strong	Strong	strong to very strong	Very Strong	very strong to extreme	Extreme	
Economic			X															Social
Economic							X											Environmental
Economic					X													Technological
Social											X							Environmental
Social									X									Technological
Environmental					X													Technological

- ❑ Each expert will compare the main criteria and sub-criteria against each other
- ❑ Then compare the HPT considering the sub-criteria
- ❑ Finally, aggregation of individual analysis and calculation of the final score



Step 6: Aggregation of Individual Results





Conclusion

Evaluation of Hydrogen Production Technology in Egypt

FAHP Model

- This study presents a framework for the **evaluation and prioritization of HPTs** using the FAHP method, considering sustainability dimensions (economic, env., social, and tech.).

- A comprehensive literature review identified the most applicable **evaluation criteria** which were then evaluated by a group of experts.

- A group of decision-makers decided the **Main-criteria and sub-criteria weights** applied in our case study.

- In our evaluation of the proposed ranking methodologies, PV Electrolysis scored the best HPT in Egypt, followed by Grid Electrolysis and Steam Methane reforming. While Wind Electrolysis and Biomass gasification (BG) get the lowest score

Benefits of Hydrogen development for Egypt

Economic
- Contribution to GDP growth
- Investment attractions
- Contribution to E-Hub strategy

Social
- Employment opportunities
- National competencies
- Knowledge transfer

Environment
- Contribution to Net-Zero
- Open the potential of RE
- Decarbonise heavy-intensive industries
- By reducing reliance on fossil fuels

Technological
- Know-How Transfer
- R&D opportunities
- Energy storage and grid stabilization

شكراً

ありがとうございました

Thank You