Optimization of Nuclear Energy for Sustainable Development and Climate Change Mitigation in Egypt

Nahla A. Ismaiel [1*], A.F. Farrag[2]

[1] Radiation Protection Department, Nuclear Power Plants Authority (NPPA), Cairo, Egypt.

[2] Sitting Department, Nuclear Power Plants Authority (NPPA), Cairo, Egypt.

* Corresponding author; Nahla A. Ismaiel (nahlau492@gmail.com)

Abstract: Electricity generation and use are responsible for approximately 40% of global CO_2 emissions, presenting a critical challenge in the fight against climate change. As global electricity needs continue to rise, transitioning to low-carbon electricity generation becomes imperative. This paper explores Egypt's energy transition strategies, focusing on the potential of nuclear energy and renewables to achieve a sustainable, low-carbon future. By examining Egypt's current energy landscape, CO_2 emissions profile, and potential energy scenario, the research highlights the strategic importance of integrating nuclear power and renewable energy sources to mitigate climate change and support economic development. Also suggest, Nuclear Fusion Power Plants and SMRs technologies as a source of electrical energy, with no CO_2 or other harmful atmospheric emissions for Egypt's industrial energy demands and water scarcity challenges, supporting sustainable development and energy.

Keywords: Nuclear Power Plants; CO_2 Emissions; Greenhouse Gases; Climate Change; Sustainable Development.

1. Introduction

As the world faces unprecedented challenges posed by climate change, countries are increasingly recognizing the necessity of transparent and accountable reporting mechanisms to assess their climate actions and commitments. In this context, Egypt has taken significant steps to align its national policies with international agreements, particularly the Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC) [1]. Climate change has led to an urgent need for sustainable energy solutions. The Paris Agreement aims to limit the rise of global temperature, necessitating a transition to low-carbon energy [4]. Egypt's energy sector is currently fossil-fuel-dependent, contributing significantly to CO_2 emissions. Vision 2030 aims to integrate renewable and nuclear energy to ensure energy security and sustainability [5].

In 2023, Egypt emitted 300 million tons (Mt) of CO_2, ranking 27th among the world's nations in energy-related CO_2 emissions. This accounted for 0.75% of global emissions, with per capita emissions of 3.0 tons [6]. In Egypt's current emissions profile, the electrical power generation sector stands as the largest contributor, accounting for 40% of the country's total CO_2 emissions.

Transportation emerges as the second-largest source at 20%, while industrial activities generate 15% of emissions. Residential buildings have a relatively smaller impact at 5%, with various other sectors collectively responsible for the remaining 20% of CO_2 emissions [7]. This heavy dependence on fossil fuels necessitates urgent action to transition toward cleaner energy sources.

The energy sector is pivotal in shaping Egypt's sustainable development. Given its growing population and increasing energy demand, ensuring a reliable and sustainable power supply is a national priority. Egypt is implementing a range of mitigation strategies to combat climate change and ensure long-term sustainability. Significant investments are being made in renewable energy projects, alongside efforts to reduce fuel consumption through energy sector reforms [1]. Egypt is also prioritizing energy efficiency enhancements and transitioning towards renewable fuels to reduce greenhouse gas emissions. The country has explored various strategies to mitigate emissions, including expanding renewable energy projects and incorporating nuclear energy into the national grid.

Nuclear energy is already the second-largest source of clean, dispatchable baseload power, with benefits for energy security. The key role of nuclear energy is achieving global net-zero greenhouse gas emissions/carbon neutrality by or around mid-century, keeping a 1.5°C limit on temperature rise within reach, and achieving the Sustainable Development Goal [2]. New nuclear technologies could occupy a small land footprint and can be sited where needed, partner well with renewable energy sources, and have additional flexibilities that support decarbonization beyond the power sector, including hard-to-abate industrial sectors [3]. The El-Dabaa Site was selected as the first nuclear power plant in Egypt based on many criteria relating to safety, environment, and socio-economy [8]. By 2028, the facility is expected to generate 4,800 MW of electricity, significantly reducing the country's reliance on fossil fuels, and will share in monitoring climate change and tackling its impacts [9].

The main issues are environmental pollution, the high cost of air treatment, and the high cost of energy production. An essential solution is using renewable energy instead of traditional energy (petroleum, coal, natural gas, and electric power). However, challenges persist in transitioning to nuclear power, including high initial investment costs, regulatory complexities, and public concerns regarding safety and environmental impact. Effective policy frameworks, technological advancements, and public awareness initiatives are crucial for ensuring the effective incorporation of nuclear energy into Egypt's energy portfolio.

This paper evaluates how nuclear energy could contribute to emission reductions, enhancing grid stability, and driving industrial development. By examining the scenario of an integrated low-carbon energy system (Nuclear, renewables, and hydrogen), this study aims to provide insights into optimizing Egypt's energy strategy to align with global sustainability goals while ensuring economic growth and energy security.

2. Reducing CO_2 Emissions from Egypt's Electricity Sector

Egypt faces the dual challenge of meeting rising electricity demand and reducing carbon emissions, as outlined in its Vision 2030 and international climate commitments. Historically reliant on fossil fuels, the electricity sector accounts for a significant share of national CO_2 emissions. To align with its goal of achieving 42% renewable energy by 2035 and integrating nuclear power [12], Egypt is pursuing a three-pronged strategy: transitioning to low-carbon energy, modernizing fossil fuel infrastructure, and enhancing energy efficiency. Egypt's path to a low-carbon electricity sector relies on synergizing renewable energy expansion, strategic modernization of fossil assets, and rigorous efficiency measures. Policy frameworks, international collaboration, and private-sector engagement are vital to overcoming financial and technical hurdles. By diversifying its energy mix and optimizing consumption, Egypt can meet climate targets, enhance energy security, and foster sustainable economic growth, turning Vision 2030 into reality. According to the latest report, Egypt's energy consumption increased by 3.5 kilowatt-hours by 2020 compared to 3.9 kilowatt-hours by 2023 [10,11], as shown in Figure 1, an indicator of the increasing CO_2 emissions from the electricity sector.

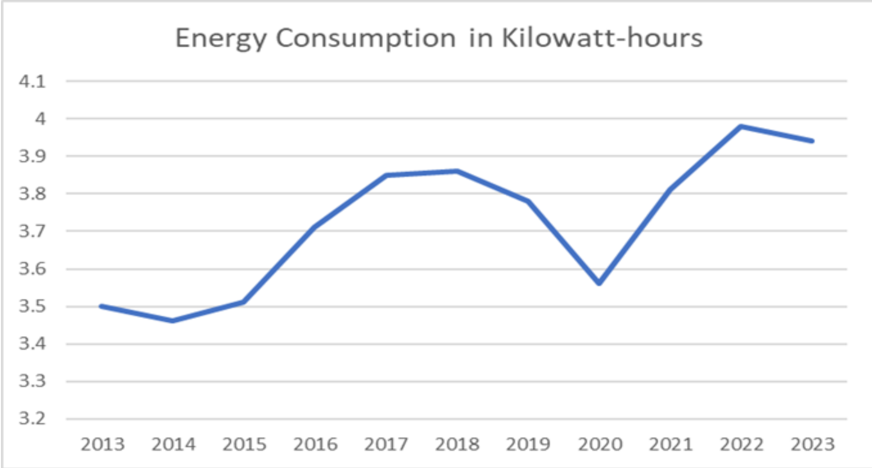

Figure 1. Energy Consumption (Kilowatt-hours) between 2013 and 2023

A shift toward renewables and nuclear energy is central to Egypt's decarbonization efforts. The country's geography offers immense solar, wind, and hydropower potential. The Benban Solar Park, one of the world's largest photovoltaic installations with a 1.8 GW capacity, exemplifies progress in solar energy. Wind farms along the Red Sea coast, where wind speeds average 10 m/s, are expanding, with the Gulf of Suez hosting 550 MW of operational projects. Hydropower, primarily from the Aswan High Dam (2.8 GW), remains a stable renewable source [13].

Nuclear energy is also critical. The El Dabaa nuclear power plant, under construction with Rosatom, will add 4.8 GW of zero-emission capacity by 2030. While natural gas—a cleaner fossil fuel—is a transitional energy source, Egypt's Vision 2030 prioritizes phasing out carbon-intensive fuels [9]. Challenges such as grid integration of variable renewables and securing investment necessitate partnerships with entities like the International Finance Corporation (IFC), which supported Benban.

Egypt is retrofitting existing gas-fired plants with combined cycle technology (CCT) to bridge the transition. This method captures waste heat from gas turbines to generate additional electricity via steam turbines, boosting efficiency from 40% to over 60%. Projects like the 4.8 GW Burullus Power Plant demonstrate this approach, reducing fuel use and emissions per unit of electricity. However, this remains an interim solution; long-term sustainability hinges on scaling renewables and nuclear energy [14].

3. The energy mix for Electricity Generation in Egypt

According to Figure 2, the most recent report of 2023, Egypt's electricity generation landscape is undergoing significant transformation. The country currently boasts an electricity-generating capacity of 189.7 Terawatt-hours, primarily derived from natural gas and renewable sources. This capacity reflects Egypt's ongoing efforts to diversify and modernize its energy infrastructure.

Egypt has ambitious plans to expand its power generation capabilities to support its development goals. The country aims to construct new power facilities with a cumulative electricity-generating capacity of 30 GW. When combined with the current 60 GW, Egypt is expected to achieve nearly 90 GW of electricity generation capacity by the year 2030. This strategic expansion represents a comprehensive approach to meeting the nation's growing energy demands [10].

The current electricity generation mix reveals the dominance of natural gas, with 178.7 Terawatt-hours in 2023, compared to 16.6 Terawatt-hours from oil. Renewable sources are gradually increasing, with hydroelectric generation at 13.8 Terawatt-hours and other renewables at 11 Terawatt-hours. Notably, nuclear energy and coal currently contribute zero Terawatt-hours, highlighting the potential for future expansion and diversification.

This comprehensive approach demonstrates Egypt's commitment to creating a sustainable, low-carbon energy future through strategic infrastructure development and innovative energy technologies [15].

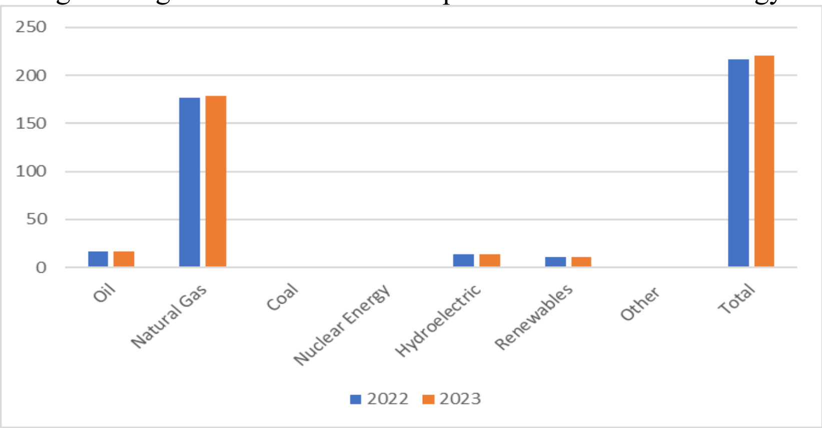

Figure 2. Electricity Generation by Fuel (Terawatt-hours) between 2022 and 2023

4. Green Scenario: A Promising Path for Egypt's Energy Transition

According to L. Abdallah et al. 2020 [6], Figure 3 presents the green (Environmental) scenario as a promising path toward Egypt's energy transition. This scenario relies on 37% renewables, 9% nuclear, and 54% natural gas. By eliminating coal from the energy mix and prioritizing low-carbon sources, this scenario significantly reduces CO_2 emissions. The transition towards cleaner energy mitigates environmental impacts and enhances long-term energy security and economic stability. Moreover, the investments in nuclear and renewable energy align with Egypt's Vision 2030 objectives, ensuring sustainability and resilience against fluctuating fossil fuel markets. The figure further illustrates the gradual increase in renewable energy adoption over the years, reinforcing the feasibility of a low-carbon energy mix.

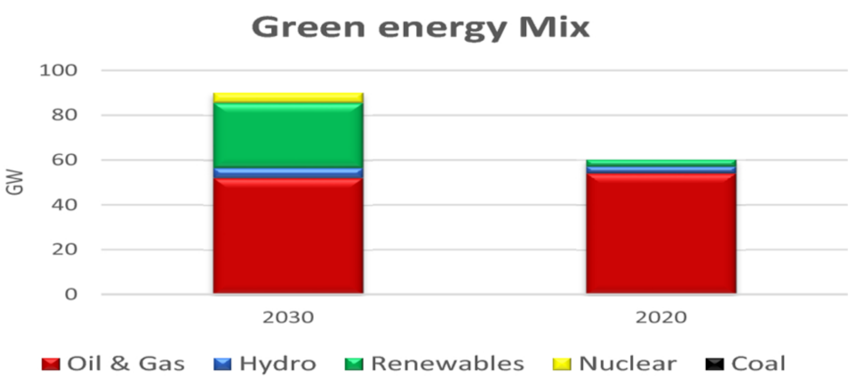

Figure 3. Green (Environmental) Scenario, copyright and permission from [6]

Quantitatively evaluates emissions and power generation under the green scenario. The data shows that by 2030, total electricity production will reach 400,367 GWh, while CO_2 emissions are expected to decline to 128,863 kilotons. This represents a significant reduction compared to other scenarios, and the data highlights the potential of nuclear energy to support clean energy transitions while maintaining grid stability. Additionally, the green scenario ensures reduced dependence on imported fossil fuels, fostering a self-sufficient and resilient energy sector. Also, noticed that CO_2 intensity decreased from 628 gCO_2/kWh in 2020 to 322 gCO_2/kWh in 2030 by adding nuclear energy and renewable energy sources as in Figure .4.

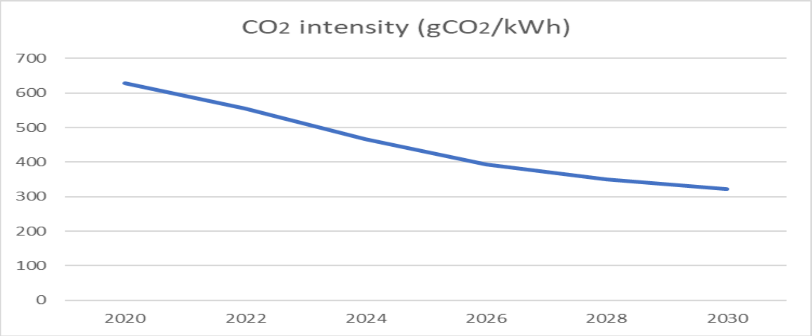

Figure 4. The intensity of CO_2 emissions between 2020 to 20230

5. Supposed Scenario: Integrated low-carbon energy system

The proposed development model focuses on an integrated low-carbon energy system that combines nuclear power, renewables, and green hydrogen technologies. This innovative approach addresses the critical challenge of reducing carbon emissions while ensuring energy security and sustainable development. Nuclear energy is divided into two parts, as a crucial element in reaching global net-zero goals involves collaborating with renewable energy sources and various low-carbon alternatives. This approach is integral to developing a sustainable energy system aimed at reducing carbon emissions in both electricity and non-electric energy production.

The first part is the El-Dabaa Nuclear Power Plant, a key environmental target to reduce the carbon intensity of electricity production dramatically. it is expected to generate 4,800 MW of electricity, significantly reducing the country's reliance on fossil fuels and producing zero CO_2 emissions [16,17]. Compared to other power plants with natural gas as fuel, it will produce 18 Mt per year of CO_2 emissions, while a power plant with coal will produce 33 Mt per year of CO_2 emissions. A power plant with petroleum as fuel will produce 25.3 Mt per year of CO_2 emissions, as shown in Figure 5.

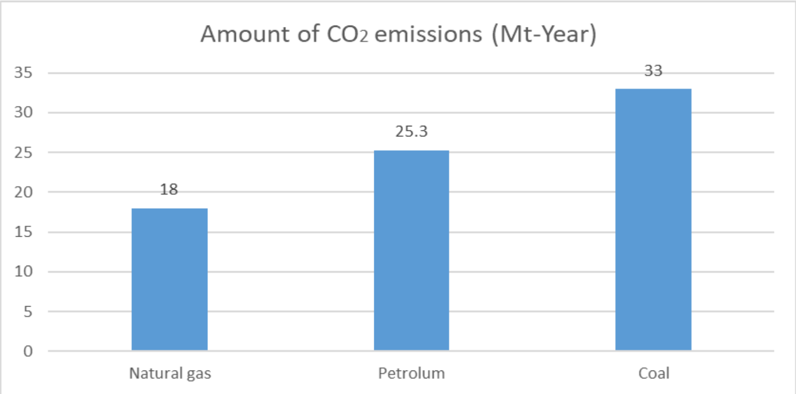

Figure 5. CO_2 emissions from the EL-Dabaa power plant will be reduced annually.

The second part is Nuclear Fusion Power Plant, in which the process by which two light atomic nuclei merge to create a single heavier nucleus while generating significant energy is known as nuclear fusion. It is considered one of the most environmentally friendly energy sources [18]. The fusion process does not produce CO_2 or any other harmful emissions, meaning it does not contribute to greenhouse gas output or global warming. Notably, CO_2 emissions from fusion reactors are lower than those from photovoltaic systems and only slightly higher than those from fission reactors.

The additional observations include: (i) The majority of CO_2 emissions from fusion reactors stem from materials. (ii) Approximately 60-70% of total CO_2 emissions arise from the construction of the reactor, while the remainder comes from its operation. (iii) The reversed shear reactor can achieve a 50% reduction in CO_2 emissions compared to the ITER-like reactor. An example of tokamak fusion reactors demonstrates their effectiveness in maintaining low CO_2 emission intensity, positioning them as a viable energy solution to combat global warming. There are essential technical requirements and key considerations for fusion power plants, such as (iii) High thermal conversion efficiency. (iii) Use of low activation materials. (iii) Implementation of passive safety and reliable containment [19].

The shift to sustainable energy requires diverse solutions, with green hydrogen emerging as a key innovation. This clean energy carrier offers transformative potential for decarbonizing multiple sectors in the transition to a low-carbon economy. Its versatility helps tackle climate change through emissions reduction while enabling clean energy integration across industries.

Green hydrogen production utilizes renewable energy-powered water electrolysis, distinguishing it from conventional hydrogen made from fossil fuels. This process eliminates greenhouse gas emissions during production, making it an environmentally sustainable alternative. This makes it a crucial component in the quest for sustainable development and reducing carbon footprints.

Furthermore, green hydrogen is a significant way of storing energy as it stores surplus renewable energy for use when demand is at its peak or during low renewable generation periods. This storage capability helps manage the intermittent nature of solar and wind power, enabling better integration of renewable sources into existing infrastructure while maintaining zero CO_2 emissions, as demonstrated in Figure 6.

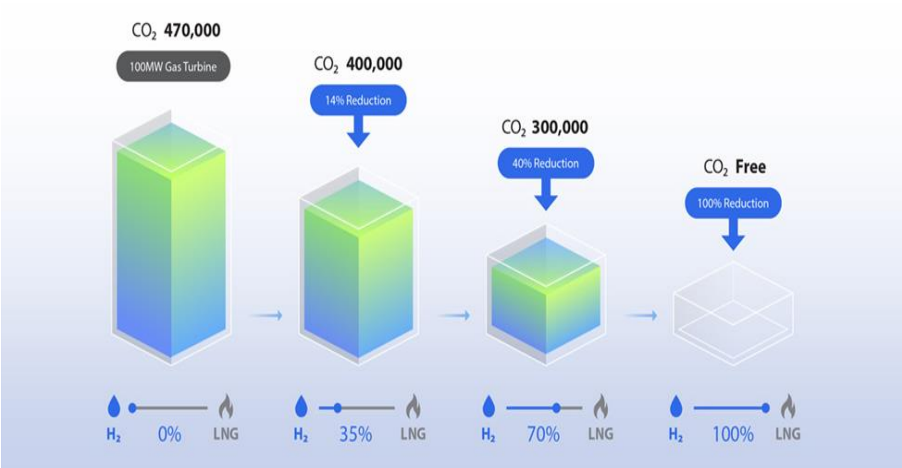

Figure 6. CO_2 emissions in tons by green hydrogen mixed gas turbines annually - copyright and permission from [25].

By replacing fossil fuels in these energy-intensive sectors, green hydrogen can have a considerable impact on the reduction of greenhouse gases and promote more sustainable industrial practices. This benefits the environment and contributes to developing a circular economy, where waste and emissions are minimized and resources are utilized more efficiently [20].

Beyond its role in industrial decarbonization, green hydrogen also holds promise in the transportation sector. With the development of hydrogen-powered fuel cell vehicles (FCEVs) and hydrogen-fueled trains, buses, and trucks, the provision of fossil fuels can also be done cleanly, using fuel-powered modes of transportation. By adopting these hydrogen-based technologies, the transportation sector can drastically reduce its carbon footprint, leading to cleaner air and a more sustainable mobility landscape. However, the widespread adoption of green hydrogen technology has its challenges.

The high costs associated with electrolysis, the need for scaling up renewable energy capacity, and the development of robust hydrogen infrastructure are some of the barriers that must be addressed. The full potential of green hydrogen cannot be utilized without certain prerequisites. There is a need for the government, the private sector, and academic research to work together in adopting new technologies, making mass production more efficient, and building needed facilities. In addition, the adoption of policies that treat the green hydrogen technology with prioritization, as well as favorable regulatory policies, will hasten the achievement of a low-carbon economy [21].

6. Conclusion

Egypt's energy strategy prioritizes emission reduction through an integrated low-carbon system combining nuclear, renewables, and green hydrogen. The plan includes El-Dabaa nuclear plant's four VVER-1200 MW units and aims to cut emission intensity from 463 g CO_2/kWh (2019) to 10-20 g CO_2/kWh by 2050, while increasing consumption to 400,000 million kWh. This aligns with Egypt's Vision 2030, Paris Agreement commitments, and addresses water scarcity through nuclear-powered desalination.

In conclusion, the development of nuclear power plants and the adoption of green hydrogen hold immense potential in advancing renewable energy and promoting sustainable development. As a clean and versatile energy source, green hydrogen is crucial for the world to utilize in mitigating climate change. Moreover, we would like to suggest expanding the Egyptian nuclear program through:

- Studying new areas suitable for establishing nuclear power plants.
- Adding Small Modular Reactors (SMRs) into Egypt's energy strategy offers a highly adaptable, low-carbon solution to meet the country's growing energy demands.
- SMRs provide flexible and scalable power generation, making them particularly advantageous for remote areas and industrial applications, which strengthening Egypt's energy security and supporting long-term sustainability.
- In the future, using nuclear fusion power plants as dependable energy-generating units, as fusion produces no CO_2 or other harmful emissions, making it a sustainable alternative that does not contribute to global warming.
- Importantly, with regard to electrical energy produced from fusion reactors, the level of CO_2 emissions is less than that of photovoltaic systems, and it is marginally greater than that of fission reactors.

References

[1]https://climate-transparency-platform.org/gef-enabling-activities/egypts-first-biennial-update-report.

[2] https://www.iaea.org/sites/default/files/21/10/nuclear-energy-for-a-net-zero-world.pdf.

[3]https://www.energy.gov/articles/cop28-countries-launch-declaration-triple-nuclear-energy-capacity-2050-recognizing-key.

[4] Santos, F. D.; Ferreira, P. L.; Pedersen, J. S. T. Climate Change 2022, 10, (5), 75.

[5] Gibson, A.; Makuch, Z.; Yeganyan, R.; Tan, N.; Cannone, C.; Howells, M. Energies 2024, 17, (10), 2397.

[6] Abdallah, L.; El-Shennawy, T. Euro-Mediterranean journal for environmental integration 2020, 5, (3), 49.

[7] Abdallah, L.; El-Shennawy, T. Journal of Engineering 2013, 2013, (1), 845051.

[8] Abudeif, A. M.; Abdel Moneim A.A. and Farrag, A, F. Multicriteria decision analysis based on analytic hierarchy process in GIS environment for siting nuclear power plant in Egypt. Ann Nucl Energy 2015;75:682–92.

[9] https:// rosatom.ru// Rosatom State Atomic Energy Corporation ROSATOM global leader in nuclear technologies, nuclear energy.

[10] https://edgar.jrc.ec.europa.eu/report_2024?vis=CO2pop#emissions.

[11] https://ourworldindata.org/CO2/country/egypt.

[12] AlMallahi, M. N.; Al Swailmeen, Y.; Abdelkareem, M. A.; Olabi, A. G.; Elgendi, M. Energy Conversion and Management: X 2024, 22, 100553.

[13] Hafner, M.; Raimondi, P. P.; Bonometti, B., Low-carbon energy strategies in MENA countries. In The Energy Sector and Energy Geopolitics in the MENA Region at a Crossroad: Towards a Great Transformation, Springer: 2023; pp 175-261.

[14] Khaleel, M.; Yusupov, Z.; Rekik, S.; Kı lı ç, H.; Nassar, Y. F.; El-Khozondar, H. J.; Ahmed, A. A. Energy Exploration & Exploitation 2025, 01445987251314504.

[15]https://www.oecd.org/en/publications/oecd-green-growth-policy-review-of-egypt-2024_b9096cec-en.html - Search (bing.com).

[16] https://www.iea.org/policies/18998-egypts-economic-strategy-for-2024-2030.

[17] https://www.iea.org/countries/egypt.

[18] https://www.iaea.org/newscenter/news/what-is-nuclear-fusion.

[19] Nagla, T. F.; ELMESAWY, M. and Ismaiel, N. A. Water coolant performance for fission and fusion reactors, The Conf. on Compatibility Between Coolants and Materials for Fusion Facilities and Advanced Fission Reactors, 2023, IAEA, Vienna, Austria.

[20] Stoica Dorel, Mihăescu Lucian, Lăzăroiu Gheorghe and Lăzăroiu George Cristian. Green hydrogen a solution for replacing fossil fuels to reduce CO2 emissions, 2024,12(8): 1651.

[21] https://www.lhyfe.com/more-about-hydrogen/5 Ways to Reduce Carbon Footprint with Green Hydrogen - Lhyfe.

[22] https://www.psm.com/news-press-release-archive/psm-thomassen-clean-energy-economy-amp-hydrogen-overview-of-2022.