

The Importance of Being Nuclear: A Quantitative Assessment of Lebanon's Energy Crisis

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Abstract

Since the 2019 crisis, Lebanon has faced a severe electricity crisis that has slowed the country's development and worsened its economic situation. This study investigates whether nuclear energy could theoretically resolve Lebanon's electricity crisis and meet national demand. In this paper, the amount of fuel needed to meet the demand was calculated, along with the CO₂ emissions, since environmental impact is an important factor. The land area required was also considered, because Lebanon is a small and densely populated country. In addition, an LCOE analysis was carried out to evaluate the economic side, especially since the crisis has already affected the country's economy. A safety comparison based on death rates was also included. The results of this study show that nuclear energy could be a suitable solution for Lebanon's electricity crisis, as it can produce a large amount of energy with very little fuel, low CO₂ emissions, and relatively small land use. It also fits the country's situation well. The LCOE analysis shows that it can be a cost-effective, long-term option, and the safety comparison suggests that it is relatively safe. Overall, nuclear energy could significantly improve Lebanon's energy situation if the right safety measures are taken.

Keywords: nuclear energy; energy crisis; electricity demand; levelized cost of electricity; environmental impact

1 Introduction

Lebanon suffers from chronic electricity shortages that affect households, hospitals, industrial activity, and critical infrastructure. Power outages are frequent, as existing energy sources fail to meet national demand. This ongoing crisis has significant economic and social consequences: it limits technological and industrial development and drives heavy reliance on private diesel generators, which add financial cost and environmental pollution. Consequently, reliable, large-scale energy solutions must be explored. This project investigates whether nuclear power plants, analyzed using fundamental physics principles, could theoretically meet Lebanon's electricity needs.

Among the proposed alternatives, nuclear energy remains one of the most energy-dense methods of electricity generation. Nuclear power plants generate energy through nuclear fission. In this process, an unstable nucleus such as uranium-235 absorbs a neutron and undergoes fission, splitting into smaller nuclei. Each fission releases energy and additional neutrons, which can induce further fission reactions, forming a controlled chain reaction capable of sustaining an extremely large number of fissions per second.

The energy released during fission is explained by the concept of mass defect in nuclear reactions, where a small amount of mass is converted into energy according to Einstein's mass-energy equivalence principle,

$$E = mc^2 \quad (1)$$

Because of the extremely high energy density of nuclear fuel, this process can generate large amounts of continuous electrical power while requiring only small quantities of fuel, resulting in a relatively low volume of physical waste by mass compared to conventional fossil-fuel energy sources. Additionally, a portion of spent nuclear fuel can be reprocessed to recover usable materials, further reducing the total volume of long-term radioactive waste. These characteristics make nuclear energy a significant subject of investigation in discussions of long-term energy security and large-scale electricity production.

2 Literature review

Lebanon's electricity sector has experienced a severe structural collapse in recent decades due to financial crisis, failures, and reliance on imported fossil fuels. The national utility, Électricité du Liban (EDL), has been unable to meet electricity demand, resulting in widespread shortages and long daily blackouts. As a result, private diesel generators have become the main alternative source of electricity, although they are costly, polluting, and unevenly accessible, increasing social inequality and economic pressure on households. Studies show that the electricity crisis intensified after the 2019 financial collapse, which led to currency devaluation, fuel shortages, and rising electricity costs. This has significantly affected living conditions, limiting access to essential services such as healthcare, education, food preservation, and water supply. The crisis therefore extends beyond infrastructure failure, representing a broader socio-economic collapse affecting households and communities across the country (Human Rights Watch, 2023).

A nuclear reactor is driven by a chain reaction, a process called fission, in which a neutron strikes an atom and causes it to split into smaller atoms, releasing energy. The resulting heat is removed from the reactor by a circulating fluid, typically water, and used to generate steam, which drives turbines to produce electricity. To keep the reaction proceeding at the correct rate, reactors are equipped with control systems that can accelerate, slow, or shut down the reaction and regulate the heat produced; this is normally done using control rods made of neutron-absorbing materials such as silver and boron. Nuclear reactors vary in shape and size, but all share the trait of being long-lasting, able to operate for up to around 80 years while continuously generating electricity. Their fuel is mainly uranium-235, though other fuels such as plutonium and thorium can also be used. Most modern reactors contain several hundred fuel assemblies, each holding thousands of small uranium fuel pellets, and a single pellet contains as much energy as approximately one tonne of coal. Like any industry, nuclear energy generates waste; however, the amount produced is relatively small and can be managed and contained, with most of it being of low radioactivity. Nuclear waste can be managed in two main ways: recycling for further energy production, or direct disposal (World Nuclear Association, 2026b).

3 Methodology

This project uses a physics-based analytical approach to evaluate whether nuclear power plants could theoretically supply Lebanon's electricity demand. For this analysis, several assumptions were made to simplify calculations and modeling. Lebanon's national electricity demand was assumed to remain constant at approximately 3 GWe. Each nuclear reactor is assumed to have a power output of 1 GWe and to operate continuously with a capacity factor of 95% (Larsen et al., 2024). Uranium-235 was assumed to be readily available as the fuel source for all reactors, and standard reactor efficiencies were applied.

Table 1.
Primary analytical parameters and baseline assumptions

Energy Source	Assumed Demand	Capacity Factor (CF)	Operational Lifetime	Overnight Capital Cost
Nuclear	3 GWe	95% (Larsen et al., 2024)	40 years (U.S. Department of Energy, 2022)	5.3 billion US dollars (Martinez & Desmarais, 2011)
Coal	3 GWe	42.5% (Statista, 2026)	35 years (Burnard et al., 2014)	10.035 billion US dollars (Prestige Investment Group, n.d.)
Diesel	3 GWe	40% (Flint Smith et al., 2025)	20 years (IMP Corporation, n.d.)	2.36 billion US dollars (Gruver, 2025)
Solar	3 GWe	26% (McHugh, n.d.)	30 years (Torres, 2025)	1.01 billion US dollars overnight (Coldwell Energy, n.d.)
Onshore	3 GWe	44% (Opoura, 2025)	25 years (Gridinta, n.d.)	3.87 billion US dollars (SolarTech, 2025)
Offshore	3 GWe	52% (Opoura, 2025)	22 years (Gridinta, n.d.)	7.2 billion US dollars (SolarTech, 2025)

This table summarizes the primary analytical parameters and baseline assumptions applied across all six energy sources evaluated in this study. It outlines the uniform national baseline demand requirement, along with technology-specific capacity factors, operational lifetimes, and overnight capital costs sourced from global industry standards. The values used for capacity factors, costs, and reactor lifetimes in this study are based on typical global data. Real conditions in Lebanon — including an older, less efficient electrical grid, higher transmission losses, different financing costs, and the current security and political situation — could change these results in practice.

The system under analysis consists of three nuclear reactors supplying electricity to the national grid, modeled as steady-state, base-load sources. Transmission and distribution losses, as well as regulatory and political constraints, are not considered, so the analysis can focus on theoretical generation capability. These assumptions and system definitions form the basis for the calculations of total electricity production, household supply, and environmental comparisons presented in later sections. All energy sources are assumed to operate continuously at their stated capacity factors, representing average annual output rather than moment-to-moment variability.

4 Results and Discussion

Lebanon's current national electricity demand is estimated to be approximately 3 GWe, and a single 1 GWe nuclear reactor operating at a 95% capacity factor can supply electricity for roughly 1 million households. Therefore, three 1 GWe nuclear reactors could theoretically meet the electricity needs of the entire country.

4.1 Energy Produced

Energy Produced per Fission

$$E_f = (200\text{MeV})(1.602 \times 10^{-13} \text{ J/MeV}) \quad (2)$$

$$E_f = 3.20 \times 10^{-11} \text{ J/ fission} \quad (3)$$

Electrical Power

$$P_e = 1.0 \times 10^9 \text{ W} = 1.0 \times 10^9 \text{ J/s} \quad (4)$$

Thermal Power (The assumed efficiency is $\eta = 33\% = 0.33$ (Feng, 2023).)

$$P_{th} = \frac{P_e}{\eta} \quad (5)$$

$$P_{th} = \frac{1.0 \times 10^9}{0.33} = 3.03 \times 10^9 \text{ J/s} \quad (6)$$

Fission Rate

$$R = \frac{P_{th}}{E_f} \quad (7)$$

$$R = \frac{3.03 \times 10^9}{3.20 \times 10^{-11}} = 9.47 \times 10^{19} \text{ fissions /s} \quad (8)$$

Energy Produced per Year

The time per year is $t = 3.1536 \times 10^7$ s, and the capacity factor is $CF = 0.95$.

$$E_y = P_e \times CF \times t \quad (9)$$

$$E_y = (1.0 \times 10^9)(0.95)(3.1536 \times 10^7) = 2.99 \times 10^{16} \text{ J/ year} \quad (10)$$

The conversion between joules and terawatt-hours is:

$$1\text{TWh} = 3.6 \times 10^{15} \text{ J} \quad (11)$$

$$E_y = \frac{2.99 \times 10^{16}}{3.6 \times 10^{15}} \approx 8.3\text{TWh/ year} \quad (12)$$

4.2 Fuel-Consumption Calculations

Number of Fissions per Day

$$N_{day} = R \times 86,400 \quad (13)$$

$$N_{day} = (9.47 \times 10^{19})(86,400) \approx 8.18 \times 10^{24} \text{ fissions / day} \quad (14)$$

Fuel Mass Consumed per Day

$$m_{day} = \frac{N_{day} M}{N_A} \quad (15)$$

where N_{day} is the number of fissions per day; $M = 235 \times 10^{-3} \text{ kg/mol}$ is the molar mass of uranium-235; and $N_A = 6.022 \times 10^{23} \text{ mol}^{-1}$ is Avogadro's constant.

$$m_{day} = \frac{(8.18 \times 10^{24})(235 \times 10^{-3})}{6.022 \times 10^{23}} \approx 3.19 \text{ kg/ day} \quad (16)$$

Annual Fuel Consumption

$$m_{year} = m_{day} \times 365 \quad (17)$$

$$m_{year} = (3.19 \text{ kg/ day})(365 \text{ days / year}) \approx 1.16 \times 10^3 \text{ kg/ year} \quad (18)$$

A single 1 GWe nuclear reactor can produce approximately 8.3 TWh per year, which is sufficient to supply a significant portion of national electricity demand. This demonstrates the high energy density of nuclear fuel, where a very small amount of U-235 can generate large-scale continuous electricity production. The reactor consumes about 3.2 kg of U-235 per day and 1.16 metric tons per year. This very small fuel requirement highlights the extremely high energy density of nuclear fuel.

Note: this 1.16 metric tons per year is the mass of U-235 that actually undergoes fission, not the total mass of reactor fuel loaded. Since commercial reactors use low-enriched uranium (LEU) at about 5% U-235, the actual mass of LEU fuel loaded each year is larger; this is

calculated later, in the Cost section, as approximately 19.1 metric tons of LEU/year using a burnup-based method. Even using this larger, more realistic figure, nuclear still requires dramatically less fuel mass than coal or diesel to produce the same electricity output. To clearly illustrate the advantages of nuclear power, it is important to compare it with other widely used energy sources from multiple perspectives, including energy and infrastructure density, environmental impact, land area, cost, and death rates.

4.3 Energy and Infrastructure Density:

Coal

Coal provides approximately 24 MJ/kg of thermal energy ("Coal," 2026). With a coal-plant efficiency of 33% (Feng, 2023), the usable electrical energy per kilogram is:

$$E_{\text{coal,usable}} = \eta_{\text{coal}} E_{\text{coal}} = (0.33)(24 \times 10^6 \text{ J/kg}) \quad (19)$$

$$E_{\text{coal,usable}} = 7.92 \times 10^6 \text{ J/kg} \quad (20)$$

$$m_{\text{coal}} / \text{year} = \frac{E_{\text{nuclear}}}{E_{\text{coal,usable}}} \quad (21)$$

$$m_{\text{coal/year}} = \frac{2.99 \times 10^{16} \text{ J/year}}{7.92 \times 10^6 \text{ J/kg}} = 3.78 \times 10^9 \text{ kg/year} \quad (22)$$

Diesel

Diesel provides approximately 43 MJ/kg of thermal energy ("Diesel Fuel," 2026). With an engine efficiency of 35% (Giddings et al., 2016), the usable electrical energy per kilogram is:

$$E_{\text{diesel,usable}} = \eta_{\text{diesel}} E_{\text{diesel}} = (0.35)(43 \times 10^6 \text{ J/kg}) \quad (23)$$

$$E_{\text{diesel,usable}} = 15.05 \times 10^6 \text{ J/kg} \quad (24)$$

$$m_{\text{diesel}} / \text{year} = \frac{E_{\text{nuclear}}}{E_{\text{diesel,usable}}} \quad (25)$$

$$m_{\text{diesel/year}} = \frac{2.99 \times 10^{16} \text{ J/year}}{15.05 \times 10^6 \text{ J/kg}} = 1.99 \times 10^9 \text{ kg/year} \quad (26)$$

Solar Panels

A single solar panel is assumed to produce 657 kWh/year under average operating conditions (Nautilus Solar, 2025).

$$N_{\text{solar}} = \frac{E_{\text{nuclear}}}{E_{\text{panel}}} \quad (27)$$

$$N_{\text{solar}} = \frac{8.3 \times 10^9 \text{ kWh/year}}{657 \text{ kWh/(panel} \cdot \text{year)}} = 1.26 \times 10^7 \text{ panels} \quad (28)$$

$\approx 12.6 \text{ million panels}$

Wind Turbines - Onshore Wind

A single onshore turbine is assumed to have a rated power of 2 MW (Business Norway, 2026) and a capacity factor of 44% (Opoura, 2025).

$$E_{\text{onshore}} = P_{\text{rated}} \times t \times \text{CF} \quad (29)$$

$$E_{\text{onshore}} = (2\text{MW})(8,760 \text{ h/year})(0.44) = 7,708.8\text{MWh/year} \quad (30)$$

$$E_{\text{onshore}} = 7.709\text{GWh/year} \quad (31)$$

$$N_{\text{onshore}} = \frac{E_{\text{nuclear}}}{E_{\text{onshore}}} \quad (32)$$

$$N_{\text{onshore}} = \frac{8,300\text{GWh/ year}}{7.709\text{GWh}/(\text{turbine} \cdot \text{year})} = 1,076.7 \approx 1,077 \text{ turbines} \quad (33)$$

Wind Turbines - Offshore Wind

A single offshore turbine is assumed to have a rated power of 8 MW (International Renewable Energy Agency, 2025) and a capacity factor of 52% (Opoura, 2025).

$$E_{\text{offshore}} = P_{\text{rated}} \times t \times \text{CF} \quad (34)$$

$$E_{\text{offshore}} = (8\text{MW})(8,760 \text{ h/ year})(0.52) = 36,441.6\text{MWh/ year} \quad (35)$$

$$E_{\text{offshore}} = 36.44\text{GWh/ year} \quad (36)$$

$$N_{\text{offshore}} = \frac{E_{\text{nuclear}}}{E_{\text{offshore}}} \quad (37)$$

$$N_{\text{offshore}} = \frac{8,300\text{GWh/ year}}{36.44\text{GWh}/(\text{turbine} \cdot \text{year})} = 227.8 \approx 228 \text{ turbines} \quad (38)$$

Table 2.

Amount of fuel/devices needed to generate 8.3 TWh/year

Type	Amount of fuel/devices
Nuclear	1.16 metric tons of U-235
Coal	3.78 million metric tons
Diesel	1.99 million metric tons
Solar panels	12.6 million solar panels
Onshore wind turbines	1,076 wind turbines
Offshore wind turbines	228 wind turbines

This table shows that nuclear energy requires a dramatically smaller amount of fuel than other energy sources. As shown, fossil fuels such as coal and diesel require millions of metric tons to match the same output, while renewable sources like solar and wind need anywhere from thousands to millions of units. This highlights the high energy density of nuclear fuel.

These results show a large difference in energy density between nuclear energy and other energy sources. A 1 GWe nuclear reactor can generate about 8.3 TWh/year while consuming only 1.16 metric tons of U-235. In contrast, coal and diesel require millions of tons of fuel to produce the same electricity output. Solar and wind also require large-scale infrastructure, including millions of panels or hundreds to thousands of turbines. This difference is due to nuclear fission releasing far more energy per unit mass than chemical or renewable conversion processes. As a result, nuclear energy provides continuous high-output electricity with minimal fuel requirements. Overall, nuclear energy demonstrates a clear advantage in energy density compared to all other sources considered.

4.4 Environmental impact:

When evaluating different energy sources, environmental impact is an important factor. One key indicator is the amount of CO₂ emitted per unit of usable electrical energy produced.

Nuclear:

Nuclear energy emits approximately 12g/kWh of CO₂ (Cabrera, n.d.). A 40-year reactor lifetime is assumed (U.S. Department of Energy, 2022).

$$\begin{aligned} \text{CO}_2 \text{ emissions/year} &= \text{CO}_2 \text{ released per kg} \\ &\text{during a life cycle} \times \text{mass of U235/year} = 0.012 \\ \text{kg / kWh} \times 8.3 \times 10^9 \text{ kWh} &= 9.96 \times 10^7 \text{ kg/year} \end{aligned} \quad (39)$$

$$\begin{aligned} &\text{Lifetime (40 years) CO}_2 / \text{nuclear reactor} \\ &= 9.96 \times 10^7 \text{ kg/year} \times 40 \text{ years} = 3.98 \text{ million tons over 40 years} \end{aligned} \quad (40)$$

Coal:

For every kilogram of coal burned, 2.46 kg of CO₂ is released (Yu et al., 2014).

$$\begin{aligned} \text{CO}_2 \text{ emissions /year} &= \text{CO}_2 \text{ released per kg of} \\ &\text{coal} \times \text{mass of coal/year} = 2.46 \text{ kg} \times 3.78 \times 10^9 \text{ kg} \\ &= 9.29 \times 10^9 \text{ kg of CO}_2 / \text{year} \end{aligned} \quad (41)$$

$$\begin{aligned} &\text{Lifetime (35 years) (Burnard et al. , 2014) CO}_2 / \text{coal} = \\ &9.29 \times 10^9 \\ &\text{kg of CO}_2 / \text{year} \times 35 \text{ years} = 3.25 \times 10^{11} \text{ kg of CO}_2, \\ &\text{which is about 325 million tons of} \\ &\text{CO}_2 \text{ over 35 years.} \end{aligned} \quad (42)$$

Diesel:

$$\begin{aligned} \text{CO}_2 \text{ per kg diesel} &= \text{CO}_2 / \text{liter} / \text{mass/ liter} = 2.6 \\ &\text{kg (Sajdl, n. d.)} / 0.835 = 3.11 \text{ kg CO}_2 / \text{kg} \end{aligned} \quad (43)$$

$$\begin{aligned} \text{CO}_2 / \text{year} &= 3.11 \text{ kg CO}_2 / \text{kg} \times 1.99 \times 10^9 \text{ kg} = 6.19 \\ &\times 10^9 \text{ CO}_2 / \text{year} \end{aligned} \quad (44)$$

$$\begin{aligned} &\text{Lifetime (20 years) (IMP Corporation, n. d.) CO}_2 / \text{diesel} = \\ &6.19 \times 10^9 \\ &\text{CO}_2 / \text{year} \times 20 \text{ years} = 1.238 \times 10^{11} \text{ kg of CO}_2. \end{aligned} \quad (45)$$

Solar panels:

Solar panels produce approximately 41 g of CO₂ per 1 kWh of electricity generated (Wigness, 2025).

$$\begin{aligned} \text{CO}_2 \text{ per panel/year} &= 657 \text{ kWh/year} \times 41 \text{ g CO}_2 / \text{kWh} = 26.9 \text{ kg} \\ &\text{CO}_2 / \text{year per panel} \end{aligned} \quad (46)$$

$$\begin{aligned} &\text{CO}_2 \text{ per total number of panels / year} = 12.6 \text{ million} \\ &\times 26.9 \text{ kg CO}_2 / \text{year per panel} = 338.94 \text{ thousand tons} \\ &\text{CO}_2 / \text{year, which rounds up to 339 thousand tons} \end{aligned} \quad (47)$$

$$\begin{aligned} &\text{Lifetime (30 years) (Torres, 2025) CO}_2 / \text{solar panel} = 339 \\ &\text{thousand tons CO}_2 / \text{year} \times 30 \text{ years} = 10.17 \text{ million tons of CO}_2 \\ &\text{over 30 years} \end{aligned} \quad (48)$$

Wind turbine:

Onshore: It approximately produces 11g of CO₂/ kWh (Business Norway, 2025).

$$\begin{aligned} \text{CO}_2 \text{ per wind turbine/year} &= 7.709 \times 10^6 \\ &\text{kWh/year} \times 11 \text{ g CO}_2 / \text{kWh} = 84.799 \text{ tons/year per turbine} \end{aligned} \quad (49)$$

$$\begin{aligned} &\text{CO}_2 \text{ per total number of turbines/year} = 84.799 \\ &\text{tons/year per turbine} \times 1,076 \text{ wind turbines} = 91.2 \text{ thousand} \\ &\text{tons of CO}_2 / \text{year} \end{aligned} \quad (50)$$

$$\begin{aligned} &\text{Lifetime (25 years average) (Gridinta, n. d.) CO}_2 / \text{wind} \\ &\text{turbine} = 91.2 \text{ thousand tons of CO}_2 / \text{year} \times 25 \text{ years} = 2.28 \\ &\text{million tons of CO}_2 \text{ over 25 years} \end{aligned} \quad (51)$$

Offshore: It approximately produces 14g of CO₂/ kWh (Business Norway, 2025)

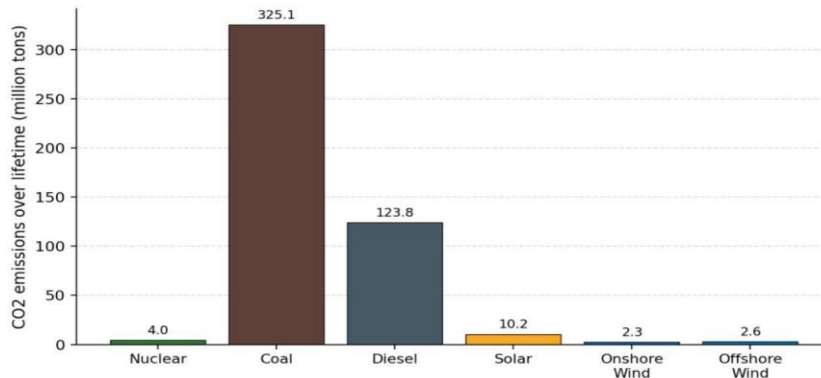
$$\begin{aligned} \text{CO}_2 \text{ per wind turbine/year} &= 36.44 \times 10^6 \\ &\text{kWh/year} \times 14 \text{ g of CO}_2 / \text{kWh} = 510.16 \text{ tons/year per turbine} \end{aligned} \quad (52)$$

$$\begin{aligned} &\text{CO}_2 \text{ per total number of turbines/year} = 510.16 \text{ tons/year per turbine} \times \\ &228 \text{ wind turbines} = 116.3 \text{ thousand tons of CO}_2 / \text{year} \end{aligned} \quad (53)$$

$$\begin{aligned} \text{Lifetime (22 years average) (Gridinta, n. d.) CO}_2/\text{wind} \\ \text{turbine} &= 116.3 \text{ thousand tons of CO}_2/\text{year} \times 22 \text{ years} = 2.558 \text{ million tons} \\ &\text{of CO}_2 \text{ over 22 years.} \end{aligned} \quad (54)$$

Figure 1.

CO₂ Emissions Over Lifetime by Energy Source



As shown in the graph, coal and diesel produce significantly higher CO₂ emissions than nuclear energy. Although renewable energy sources produce low direct emissions, once scaled up to large systems, the emissions from building and maintaining the infrastructure become noticeable. The results show a clear difference in greenhouse gas emissions between nuclear energy and other electricity generation sources when evaluated over a full life cycle. Nuclear energy has very low CO₂ emissions, producing approximately 3.98 million tons over a 40-year lifetime for the same electricity output, mainly due to emissions from construction, fuel processing, and mining rather than operation. In comparison, coal and diesel produce extremely high emissions, reaching hundreds of billions of kilograms of CO₂ over their lifetimes due to continuous fuel combustion. Renewable energy sources such as solar and wind produce zero operational emissions but still generate measurable life-cycle emissions from manufacturing, installation, and infrastructure scaling. Even at large deployment levels, solar and wind remain significantly lower in emissions than fossil fuels but higher than nuclear energy when scaled to equivalent electricity production. Overall, nuclear energy demonstrates one of the lowest life-cycle CO₂ footprints among all major energy sources while maintaining continuous large-scale electricity generation. This makes it a strong low-carbon option in the context of reducing environmental impact from electricity production.

Note: Lifetime values are based on typical global operational ranges for each technology as reported in industry sources.

4.5 Land area

Another important aspect to consider is land area. When comparing different energy sources, it is necessary to evaluate the amount of land each one requires to produce the same amount of electricity. Different energy technologies require different infrastructure, which occupies different amounts of land. This comparison helps show how much land each energy source requires to generate an equivalent electricity output.

Nuclear:

Nuclear power plants are very land-efficient. A typical 1 GWe nuclear facility requires about 1.3 square miles of land (Sustainability Directory, 2025).

$$1 \text{ square mile} = 2.59 \text{ square kilometers} \quad (55)$$

$$\text{Then a single GWe nuclear power plant} \quad (56)$$

facility requires $1.3 \times 2.59 = 3.367 \text{ km}^2$

Coal:

Coal has a capacity factor of 42.5% (Statista, 2026).

$$\text{Installed Capacity} = 8,300,000 / (0.425 \times 8760) \quad (57)$$

For coal, the area is 0.7 acres per MW (Jacobson, 2025).

$$1 \text{ acre} = 0.00405 \text{ km}^2 \quad (58)$$

$$0.7 \times 0.00405 = 0.002835 \text{ km}^2 \quad (59)$$

$$\text{Land required} = 2,230 \text{ MW} \times 0.002835 \text{ km}^2 = 6.32205 \text{ km}^2 \quad (60)$$

Diesel:

Diesel has a capacity factor of 40% (Flint Smith et al., 2025).

$$\text{Installed Capacity} = 8,300,000 / (0.40 \times 8760) = 2,368.7 \text{ MW installed} \quad (61)$$

For diesel, the area is 0.88 ha per MW (UNEP Copenhagen Climate Centre, n.d.).

$$1 \text{ ha} = 0.01 \text{ km}^2 \quad (62)$$

$$0.88 \text{ ha} \times 0.01 = 0.0088 \text{ km}^2/\text{MW} \quad (63)$$

$$\text{Land required} = 0.0088 \text{ km}^2/\text{MW} \times 2,368.7 \text{ MW} = 20.84 \text{ km}^2 \quad (64)$$

Solar panels:

Solar panels have a capacity factor of 26% (McHugh, n.d.)

$$\begin{aligned} \text{Installed Capacity} &= 8,300,000 / (0.26 \times 8760) \\ &= 3,644.18 \text{ MW installed} \end{aligned} \quad (65)$$

For solar panels, the area is 6 acres per megawatt (MW) (Powertech Energy, 2026)

$$6 \times 0.00405 = 0.0243 \text{ km}^2/\text{MW} \quad (66)$$

$$\text{Land required} = 0.0243 \text{ km}^2/\text{MW} \times 3,644.18 \text{ MW} \quad (67)$$

Wind turbines:

Onshore: They have a capacity factor of 44% (Opoura, 2025)

$$\begin{aligned} \text{Installed Capacity} &= 8,300,000 / (0.44 \times 8760) \\ &= 2,153.38 \text{ MW installed} \end{aligned} \quad (68)$$

For onshore wind, the area is 5.2 hectares per MW of installed capacity (Greiser, 2024).

$$5.2 \times 0.01 = 0.052 \text{ km}^2/\text{MW} \quad (69)$$

$$\text{Land required} = 0.052 \text{ km}^2/\text{MW} \times 2,153.38 \text{ MW} \quad (70)$$

Offshore: They have a capacity factor of 52% (Opoura, 2025)

$$\begin{aligned} \text{Installed Capacity} &= 8,300,000 / (0.52 \times 8760) = \\ &1,822.0934317 \text{ MW installed} \end{aligned} \quad (71)$$

For offshore wind turbines, the situation is different since they are installed in water rather than on land. As a result, land area is not the relevant metric; instead, the appropriate measure is the spacing area required per MW of installed capacity.

The installed power density (how much power capacity is installed per unit area) is 7 MW/km² (Enevoldsen & Jacobson, 2021)

$$\text{Then the spacing area per MW} = 1/7 \text{ km}^2/\text{MW} = 0.142 \text{ km}^2/\text{MW} \quad (72)$$

$$\text{Spacing area required} = 0.142 \text{ km}^2/\text{MW} \times 1,822.0934317 \text{ MW installed} = 258.73 \text{ km}^2 \quad (73)$$

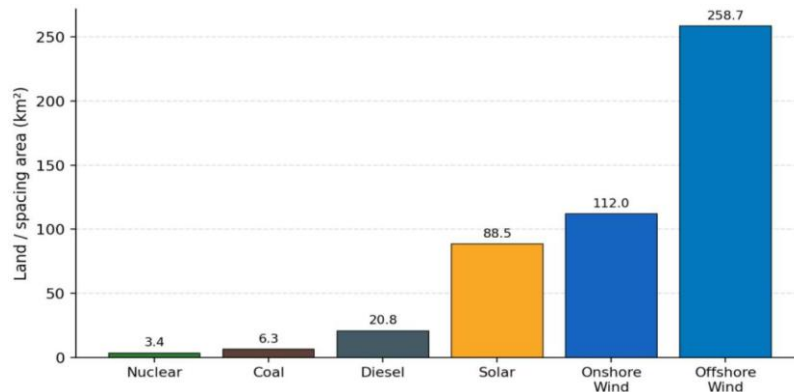


Figure 2.
Land / Spacing Area Required by Energy Source

This document shows that nuclear energy has a huge land area advantage, while other energy sources require more land especially renewable energy sources. These results show major differences in land requirements between energy sources. Nuclear energy requires the smallest land area, with a 1 GWe reactor occupying only about 3.37 km² while producing 8.3 TWh/year of electricity. Fossil fuel systems such as coal and diesel require larger areas due to fuel handling and plant infrastructure, while renewable energy systems require significantly more space because of their lower power density and capacity factors. Solar and onshore wind require tens to hundreds of square kilometers to match the same electricity output. Offshore wind also requires very large spacing areas to avoid turbine interference and maintain efficiency. Overall, nuclear energy demonstrates a major land-use advantage for large-scale electricity generation, which is especially important for geographically small and densely populated countries such as Lebanon. Note: Due to limited diesel-specific data for a 1000 MW plant, a capacity factor of 40% was conservatively applied from light fuel oil standalone generators (1 kW).

4.6 Cost

Another important factor when comparing energy sources is the cost of electricity generation. Each source requires different technologies, operations, and maintenance, which affect the overall economic feasibility of producing electricity.

Nuclear:

First of all, to build a single GWe nuclear reactor its estimated to cost 5.3 billion US dollars overnight (Martinez & Desmarais, 2011). The uranium is mined then milled (U.S. Department of Energy, n.d.-a). The cost of mining one pound of uranium oxide (yellow cake) is 23\$ (Das, 2025). Then the full cost of mining 1 kg of yellow cake is 50.7\$. Most commercial reactors use low-enriched uranium (LEU) below five percent as fuel (U.S. Department of Energy, 2025).

Now how much U-235 does 1kg of yellow cake contain:

$$\text{Yellowcake} = \text{U}_3\text{O}_8 \quad (75)$$

$$3 \text{ U atoms} = 3 \times 238 = 714 \text{ atomic mass unit (U total)} \quad (76)$$

$$8 \text{ oxygen atoms} = 8 \times 16 = 128 \text{ atomic mass unit} \quad (77)$$

$$\text{Total mass} = 714 + 128 = 842 \text{ u} \quad (78)$$

$$\% \text{ U} = 714 / 842 = 0.847 \rightarrow 84.7\%, \text{ which rounds to } 85\% \quad (79)$$

So 1 kg of yellow cake has 0.85 kg of U in it, which is mostly U-238 with roughly 0.711% of U-235 (U.S. Department of Energy, n.d.-a).

$$\text{Mass of U-235} = 0.85 \times 0.00711 (0.711/100) = 0.0060435 \text{ kg} \rightarrow 6.04 \text{ g of U-235 per kg of yellow cake} \quad (80)$$

$$\text{The U-235 needed} = 1\text{kg} \times 5\% = 1000\text{g} \times 0.05 = 50 \text{ g of U-235 per kg to reach the 5\% LEU goal} \quad (81)$$

But the total U-235 in feed is 6.04g per kg of yellow cake, so enrichment is needed. Enrichment is not 100% efficient; 0.3% of U-235 remains in the waste (tails) (U.S. Nuclear Regulatory Commission, 2026).

$$\text{Feed Mass (F)} = \text{Product Mass (P)} \times (x_p - x_t) / (x_n - x_t) \quad (82)$$

Where: F is the kg of natural uranium feed needed P is the kg of enriched uranium needed (1 kg) x_p : U-235 fraction in product (0.05) x_n : U-235 fraction in natural uranium (0.00711) x_t : U-235 fraction left as waste (0.003)

$$F = 1 \text{ kg} \times (0.05 - 0.003) / (0.00711 - 0.003) = 11.43 \text{ kg pure feed is needed} \quad (83)$$

$$\text{Yellow cake needed for 1kg of LEU} = 11.43 \text{ kg} / 0.85 = 13.44 \text{ kg} \quad (84)$$

$$\text{Cost of 1kg of LEU enriched U-235} = 13.44 \times 50.7 \text{ \$/kg} = 681.408 \text{ \$/kg} \quad (85)$$

After that yellowcake is converted into uranium hexafluoride (World Nuclear Association, 2025).

$$13.44 \times 0.85 = 11.43 \text{ kg pure uranium metal} \quad (86)$$

Each uranium hexafluoride molecule has one U atom and six F atoms

$$\text{U atomic mass} = 238 \quad (87)$$

$$\text{F atomic mass} = 19 \times 6 = 114 \quad (88)$$

$$\text{Total mass} = 352 \quad (89)$$

$$\text{Theoretical yield} = \text{Uranium mass} \times (\text{UF}_6 \text{ molar mass} / \text{U molar mass}) \quad (90)$$

$$11.42 \text{ kgU} \times (352/238) = 11.42 \times 1.479 = 16.89 \quad (91)$$

But the efficiency is 99% (Fowler, 1957)

$$16.89 \text{ kg} \times 99\% = 16.89 \times 0.99 = 16.72 \text{ kg UF}_6 \text{ produced} \quad (92)$$

$$\text{Cost of turning yellowcake into UF}_6 = 35\text{\$/kgU} \times 11.42 \text{ kg U} = 399.7 \text{ \$, rounds to } 400\$ \quad (93)$$

UF₆ gas from conversion is fed into centrifuges to increase the U-235 isotope fraction from 0.7% (natural) to 5% for typical LEU fuel. This is called enrichment (World Nuclear Association, 2025). This is measured in SWU not kg.

A kilogram of LEU requires roughly 11.43 kilograms U as feedstock for the enrichment process and about 7 separative work units (SWUs) worth of enrichment services (Neff, 1998). Each SWU cost 90\\$/SWU (Neff, 1998).

$$\begin{aligned}\text{So the cost of enrichment} &= 7 \text{ SWUs} \times 90 \text{ \$ / SWU} \\ &= 630\$ \text{ to produce 1 kg of LEU U-235}\end{aligned}\quad (94)$$

After these steps fuel fabrication takes place (World Nuclear Association, 2025): The enriched UF_6 gas is converted into uranium dioxide (UO_2) powder, which is pressed into small ceramic pellets. These pellets are then hardened by sintering at high temperatures, stacked into zirconium alloy tubes to form fuel rods, and finally assembled into fuel assemblies ready for use in a nuclear reactor.

Fuel fabrication for 1kg of LEU costs about 300\$ (World Nuclear Association, 2026a) Therefore, the total cost to produce 1kg of

$$\begin{aligned}\text{LEU (reactor fuel)} &= 681.408\$ + 400\$ + 630\$ + 300\$ \\ &= 2,011.408\$\end{aligned}\quad (95)$$

The annual cost of nuclear fuel:

$$\begin{aligned}\text{Mass of LEU/year (simple enrichment-fraction} \\ \text{estimate)} &= 1,160 \text{ kg of U-235} / 0.05 = 23.2 \text{ metric tons of LEU/year.}\end{aligned}\quad (96)$$

This method assumes all loaded U-235 undergoes fission before the fuel is discharged, which is not physically realistic: in practice, fuel is discharged once it reaches a set burnup, well before all of its U-235 is used up. A more standard approach estimates annual fuel mass directly from burnup - the amount of energy extracted from the fuel before it is removed from the reactor:

$$\begin{aligned}\text{Mass of LEU/year} &= \text{Pth} \times \text{CF} \times \text{days/year} / \text{burnup} \\ &= 3.03 \text{ GW} \times 0.95 \times 365 \text{ days/year} / 55 \text{ GWd/t} \\ (\text{World Nuclear Association, 2025}) &= 19.1 \text{ metric tons of LEU/year.}\end{aligned}\quad (97)$$

This burnup-based figure is used for the remainder of the cost analysis below, and the same annual mass is reused later in Radioactive Waste Management to estimate total waste produced.

$$\begin{aligned}\text{Then the annual cost of nuclear fuel} &= 19.1 \\ \text{metric tons of LEU/year} \times 2,011.408 \text{ \$ / kg} &= 38,417,892.8 \text{ \$}\end{aligned}\quad (98)$$

This indicates that the cost of nuclear power fuel is roughly 38.42 million dollars per year. Amount of electricity produced over the

$$\begin{aligned}\text{Amount of electricity produced over the lifetime of the reactor} &= 8.3 \\ \text{TWh/year} \times 40 \text{ years} &= 332 \text{ TWh electricity produced over the lifetime} \\ \text{of the reactor. Cost of fuel over the lifetime of the reactor} &= 38.42 \text{ million} \\ \text{dollars per year} \times 40 \text{ years} &= 1.537 \text{ billion US dollars}\end{aligned}\quad (99)$$

But it isn't that simple, because there are still the fixed and variable operation and maintenance costs, in addition to the decommissioning and financing costs.

$$1000\text{MW} \times 1000 = 1000000\text{kWe} \quad (100)$$

$$\begin{aligned}\text{Fixed O and M per year} &= \$25/\text{kWe (Larsen et al., 2024)} \times 1000000 \\ \text{kWe} &= 25 \text{ million US dollars/year}\end{aligned}\quad (101)$$

$$\begin{aligned}\text{Fixed O and M over its lifetime} &= 25 \text{ million} \\ \text{US dollars} \times 40 \text{ years} &= 1 \text{ billion US dollars}\end{aligned}\quad (102)$$

$$\begin{aligned}\text{Variable O and M per year} &= \$9.25/\text{MWh (Larsen et al., 2024)} \times 8,300,000 \\ \text{MWh} &= 76,775,000\text{US dollars} \approx 76.8 \text{ million US dollars}\end{aligned}\quad (103)$$

$$\begin{aligned} \text{Variable O and M over its lifetime} &= 76.8 \\ \text{million US dollars} \times 40 \text{ years} &= 3.071 \text{ billion US dollars} \end{aligned} \quad (104)$$

$$\begin{aligned} \text{Decommissioning over its lifetime} &= \$750/\text{kWe} \\ (\text{Larsen et al., 2024}) \times 1000000 \text{ kWe} &= 750 \text{ million US dollars} \end{aligned} \quad (105)$$

Given Lebanon's ongoing economic recovery from the 2019 crisis, unsubsidized financing (1.4× multiplier) is applied rather than Vogtle's subsidized (1.23× multiplier) (Shirvan, 2024).

$$\begin{aligned} \text{Financed Capital: the cost to build a GWe nuclear reactor overnight} \times 1.4 \\ \text{unsubsidized assumption} &= 5.3 \text{ billion US dollars} \times 1.4 \text{ unsubsidized} \\ \text{assumption} &= 7.42 \text{ billion US dollars} \end{aligned} \quad (106)$$

$$\begin{aligned} \text{Total cost} &= \text{Cost of fuel over the lifetime of the reactor} + \text{Fixed O and M} \\ &\text{over its lifetime} + \text{Variable O and M over its lifetime} + \text{Decommissioning} \\ &\text{over its lifetime} + \text{Financed Capital} = 1.537 \text{ billion US dollars} + 1 \text{ billion} \\ \text{US dollars} + 3.071 \text{ billion US dollars} + 750 \text{ million US dollars} + 7.42 \text{ billion} \\ \text{US dollars} &= 13.778 \text{ billion dollars} \end{aligned} \quad (107)$$

$$\begin{aligned} \text{LCOE} &= \text{Total cost} / \text{Total electricity produced over the lifetime of the} \\ \text{reactor} &= 13.778 \text{ billion US dollars} / 332 \text{ TWh electricity produced over} \\ \text{the lifetime of the reactor} &= 13,778,000,000 / 332,000,000,000 \text{ kWh} = \\ &0.0415 \text{ \$/kWh, which means it costs about 4.2 cents/kWh} \end{aligned} \quad (108)$$

Note: This is a simplified estimate of the levelized cost of electricity (LCOE), considering only fuel costs, operation and maintenance, decommissioning, and financed capital costs. Other factors are excluded. The same simplified method will be used for all energy sources to ensure a fair comparison. Note: A simplified fuel-cost model is used for consistent comparison across technologies. Note: To ensure consistency across all technologies and due to limited availability of consistent financial assumptions across all technologies a uniform financing of 1.4 is applied.

Note: This calculation estimates natural uranium feed required to produce 1 kg of 5% LEU using a simplified SWU mass-balance model.

Coal:

The overnight cost to build a 1000 MW coal power plant is 4.5 billion US dollars (Prestige Investment Group, n.d.), but 42.5% capacity factor requires 2,230MW installed to match the output of one nuclear reactor. Fixed and variable O&M rates are from America's Power (2025).

$$\begin{aligned} \text{So, the cost for building} &= 4.5\$/\text{GW} \times 2.23 \text{ GW} \\ &= 10.035 \text{ billion US dollars.} \end{aligned} \quad (109)$$

$$\begin{aligned} \text{Annual cost of coal needed} &= 3.78 \text{ million} \\ \text{tons} \times 130 \text{ \$/ton (Trading Economics, n.d.)} &= 491.4 \text{ million US dollars} \end{aligned} \quad (110)$$

$$\begin{aligned} \text{Amount of electricity produced over the lifetime of the power plant} &= 8.3 \text{ TWh/year} \times \\ 35 \text{ years} &= 290.5 \text{ TWh.} \end{aligned} \quad (111)$$

$$\begin{aligned} \text{Cost of coal over the lifetime of the power plant} &= 491.4 \text{ million US dollars} / \text{year} \times 35 \\ \text{years} &= 17.199 \text{ billion US dollar.} \end{aligned} \quad (112)$$

$$1000 \text{ MW} \times 1000 \text{ kW/MW} = 1000000 \text{ kW} \quad (113)$$

$$2,230 \text{ MW installed} \times 1000 \text{ kW/MW} = 2230000 \text{ kW} \quad (114)$$

$$\text{Fixed O and M per year} = \$32.75/\text{kW} \times 2230000 \text{ kW} = 73 \text{ million US dollars/year} \quad (115)$$

$$\begin{aligned} \text{Fixed O and M over its lifetime} &= 73 \text{ million US dollars} \times 35 \text{ years} = 2.55 \text{ billion US} \\ &\text{dollars} \end{aligned} \quad (116)$$

$$\text{Variable O and M per year} = \$6.25/\text{MWh} \times 8,300,000 \text{ MWh} = 51.875 \text{ million US dollars/year} \quad (117)$$

$$\text{Variable O and M over its lifetime} = 51.875 \text{ million US dollars} \times 35 \text{ years} = 1.815 \text{ billion US dollars} \quad (118)$$

$$\text{Decommissioning over its lifetime} = \$466,000/\text{MW (Gold Standard, 2024)} \times 2,230 \text{ MW} = 1.039 \text{ billion US dollars} \quad (119)$$

$$\text{Financed Capital: the cost to build the coal power plant overnight} \times 1.4 \text{ unsubsidized assumption} = 10.035 \text{ billion US dollars} \times 1.4 = 14.049 \text{ billion US dollars} \quad (120)$$

$$\begin{aligned} \text{Total cost} &= \text{Cost of fuel over the lifetime of the reactor} + \text{Fixed O and M over Its lifetime} + \text{Variable O and M over its lifetime} + \text{Decommissioning over its lifetime} + \\ &\text{Financed Capital} = 17.199 \text{ billion US dollar} + 2.55 \text{ billion US dollars} + 1.815 \text{ billion US dollars} + 1.039 \text{ billion US dollars} + 14.049 \text{ billion US dollars} = 36.652 \text{ billion US dollars} \end{aligned} \quad (121)$$

$$\text{LCOE} = \text{Total cost} / \text{Total electricity produced over the lifetime of the power plant} = 36,652,000,000 / 290,500,000,000 \text{ kWh} = 0.126 \$ / \text{kWh, which means it cost 12.6 cents/ kWh.} \quad (122)$$

Diesel:

$$\begin{aligned} \text{The overnight cost to build a 1000 MW diesel power plant} &= 1.0 \text{ million/MW (Gruver, 2025)} \times 1000 \text{ MW} = 1 \text{ billion US dollars, but a 40\% capacity factor requires 2,368.7 MW installed to reach the same output of a single GWe nuclear plant.} \end{aligned} \quad (123)$$

$$\text{Then, the cost for building} = 1 \text{ billion US dollars/GW} \times 2.36 \text{ GW} = 2.36 \text{ billion US dollars.} \quad (124)$$

1 gallon of diesel weighs 3.22 kg (Home Towne Energy, 2023), with a cost of 3.54 \$/gallon (Transport Topics, 2025)

$$\text{So the cost of one kg of diesel} = 3.54 \$/\text{gallon} / 3.22 \text{ kg} = 1.09 \$/\text{kg} \quad (125)$$

$$\text{Cost per 1 ton of diesel} = 1000 \text{ kg} \times 1.09 \$/\text{kg} = 1,090 \$/\text{ton} \quad (126)$$

$$\text{Annual cost of diesel needed} = 1.99 \text{ million tons} \times 1,090 \$/\text{ton} = 2.169 \text{ billion US dollars/year, which rounds up to 2.17 billion US dollars per year} \quad (127)$$

$$\begin{aligned} \text{Amount of electricity produced over the lifetime of the power plant} &= 20 \text{ years} \\ &\times 8.3 \text{ TWh/year} = 166 \text{ TWh.} \end{aligned} \quad (128)$$

$$\text{Cost of diesel over the lifetime of the power plant} = 2.17 \text{ billion US dollar} \times 20 \text{ years} = 43.4 \text{ billion US dollar.} \quad (129)$$

$$\begin{aligned} \text{Fixed O and M per year} &= \$13,000 \text{ per MW-year (MAVS Open Press, n.d.)} \times \\ &2,368.7 \text{ MW installed} = 30.79 \text{ million US dollars/year} \end{aligned} \quad (130)$$

$$\text{Fixed O and M over its lifetime} = 30.79 \text{ million US dollars/ year} \times 20 \text{ years} = 615.8 \text{ million US dollars} \quad (131)$$

$$\text{Variable O and M per year} = \$19.68/\text{MWh} \times 8,300,000 \text{ MWh} = 163.344 \text{ million US dollars/year} \quad (132)$$

$$\begin{aligned} \text{Variable O and M over its lifetime} &= 163.344 \text{ million US dollars/ year} \times 20 \\ &\text{years} = 3.266 \text{ billion US dollars} \end{aligned} \quad (133)$$

$$\begin{aligned} \text{Decommissioning over its lifetime} &= \$103,000/\text{MW (Statista, 2016)} \times 2,368.7 \\ &\text{MW} = 243,976,100 \text{ US dollars, which rounds to 244 million US dollars} \end{aligned} \quad (134)$$

$$\begin{aligned} \text{Financed Capital: the cost to build the diesel power plant overnight} \times 1.4 \\ \text{unsubsidized assumption} = 2.36 \text{ billion US dollars} \times 1.4 \text{ unsubsidized} \\ \text{assumption} = 3.304 \text{ billion US dollars} \end{aligned} \quad (135)$$

$$\begin{aligned} \text{Total cost} = \text{Cost of fuel over the lifetime of the reactor} + \text{Fixed O and M over} \\ \text{its lifetime} + \text{Variable O and M over its lifetime} + \text{Decommissioning over its} \\ \text{lifetime} + \text{Financed Capital} = 3.304 \text{ billion US dollars} + 0.244 \text{ billion US dollars} \\ + 3.266 \text{ billion US dollars} + 0.615 \text{ billion US dollars} + 43.4 \text{ billion US dollar} = \\ 50.829 \text{ billion US dollars, which rounds to 50.8 billion US dollars.} \end{aligned} \quad (136)$$

$$\begin{aligned} \text{LCOE} = 50,829,000,000 / 166,000,000,000 = 0.306 \\ \text{\$/kWh, which means it costs about 30.6 cents/kWh.} \end{aligned} \quad (137)$$

Note: Due to limited data on large scale diesel generators, oil-based generator data was used as an approximation, since both systems operate on similar fuel and technology. The diesel O&M rates used above are from MAVS Open Press (n.d.).

Solar:

To install a 1000 MW solar farm it would cost 1.01 billion US dollars overnight (Coldwell Energy, n.d.), but with a 26% CF, it requires 3,644.18 MW installed to output the same amount as a nuclear reactor. The fixed O&M rate is from the National Renewable Energy Laboratory (2024).

$$\begin{aligned} \text{Then, the cost for installations} = 1.01 \text{ billion US dollars per GW} \\ (= 1.01 \text{ million US dollars per MW}) \times 3,644.18 \text{ MW installed} = 3.6806 \\ \text{billion US dollars.} \end{aligned} \quad (138)$$

(cost of installation include the cost of the panels)

$$\begin{aligned} \text{Amount of electricity produced over the} \\ \text{lifetime of the solar farm} = 8.3 \text{ TWh/year} \times 30 \text{ years} = 249 \text{ TWh.} \end{aligned} \quad (139)$$

$$3,644.18 \text{ MW installed} \times 1000 = 3,644,180 \text{ kW} \quad (140)$$

$$\text{Fixed O and M per year} = \$22/\text{kW} \times 3,644,180 \text{ kW} = 80.1 \text{ million US dollars} \quad (141)$$

$$\text{Fixed O and M over its lifetime} = 80.1 \text{ million US dollars} \times 30 \text{ years} = 2.4 \text{ billion US} \\ \text{dollars} \quad (142)$$

Solar panels' variable O&M costs do exist but are very small (Bartlett, 2019).

$$3,644.18 \text{ MW installed} \times 6 \text{ acres/MW} = 21,865.08 \text{ acres} \quad (143)$$

$$\text{Decommissioning over its lifetime} = 21,865.08 \text{ acres} \times \$15,000/\text{acre (Stocks \&} \\ \text{Weber, 2026)} = 327.98 \text{ million US dollars} \quad (144)$$

$$\text{Financed Capital: cost for installations} \times 1.4 \text{ unsubsidized assumption} = 5.15 \\ \text{billion US dollars} \quad (145)$$

$$\text{Total cost} = 0.328 \text{ billion US dollars} + 2.4 \text{ billion US dollars} + 5.15 \text{ billion US} \\ \text{dollars} = 7.878 \text{ billion US dollars} \quad (146)$$

$$\begin{aligned} \text{LCOE} = 7,878,000,000 / 249,000,000,000 = 0.0316 \\ \text{\$/kWh, which means 3.16 cents/kWh.} \end{aligned} \quad (147)$$

Wind turbines:

Onshore: The installation of a 1000 MW onshore wind farm would cost \$1,800 per kW installed (SolarTech, 2025), but the CF is 44% making the installed capacity reach 2,153.38 MW installed. The all-in O&M rate is from the National Renewable Energy Laboratory (2022), and the decommissioning rate is from the U.S. Department of Energy (n.d.-b).

$$\text{Therefore, the cost of installation} = \$1,800 \text{ per kW installed} \times 2,153,380 \text{ kW installed} = 3.87 \text{ billion US dollars} \quad (148)$$

(Cost of installation include the cost of the turbines)

$$\text{Amount of electricity produced over the lifetime of the wind farm} = 8.3 \text{ TWh/year} \times 25 \text{ years} = 207.5 \text{ TWh.} \quad (149)$$

$$\text{All-in O\&M per year} = \$43/\text{kW-year} \times 2,153,380 \text{ kW installed} = 92.5 \text{ million US dollars} \quad (150)$$

$$\text{All-in O\&M over its lifetime} = 92.5 \text{ million dollars} \times 25 \text{ years} = 2.3 \text{ billion US dollars} \quad (151)$$

Note: All-in O&M equals the fixed and variable together.

$$\text{Decommissioning over its lifetime} = \$195,000 \text{ per turbine} \times 1,076 \text{ wind turbine} = 209.8 \text{ million US dollars} \quad (152)$$

$$\text{Financed Capital: cost for installations} \times 1.4 \text{ unsubsidized assumption} = 5.4 \text{ billion US dollars} \quad (153)$$

$$\text{Total cost} = 5.4 \text{ billion US dollars} + 0.209 \text{ billion US dollars} + 2.3 \text{ billion US dollars} = 7.9 \text{ billion US dollars} \quad (154)$$

$$\text{LCOE} = 7,900,000,000 / 207,500,000,000 = 0.038 \text{ \$/kWh, which means 3.8 cents/kWh.} \quad (155)$$

Offshore: The installation of a 1000 MW offshore wind farm would cost \$4,000 per kW installed (SolarTech, 2025), but with a CF of 52% the installed capacity will be 1,822.0934317 MW installed. The O&M rate is from the International Renewable Energy Agency (2012).

$$\text{So, the cost of installation} = \$4,000 \text{ per kW installed} \times 1,822,093 \text{ kW installed} = 7.29 \text{ billion US dollars} \quad (156)$$

$$\text{Amount of electricity produced over the lifetime of the wind farm} = 8.3 \text{ TWh/year} \times 22 \text{ years} = 182.6 \text{ TWh.} \quad (157)$$

$$\$0.048/\text{kWh} \times 8760 \text{ hours/year} \times 0.52 = \$218.6/\text{kW-year} \quad (158)$$

$$\text{All-in O\&M per year} = \$218.6/\text{kW-year} \times 1,822,093 \text{ kW installed} = 398.3 \text{ million US dollar} \quad (159)$$

$$\text{All-in O\&M over its lifetime} = 398.3 \text{ million US dollar} \times 22 \text{ years} = 8.7 \text{ billion US dollars} \quad (160)$$

$$\text{Decommissioning over its lifetime} = \$135,000 \text{ (Kaiser \& Snyder, 2012)} \times 1,822.0934317 \text{ MW installed} = 245.9 \text{ million US dollars} \quad (161)$$

$$\text{Financed Capital: cost for installations} \times 1.4 \text{ unsubsidized assumption} = 7.29 \text{ billion US dollars} \times 1.4 \text{ unsubsidized assumption} = 10.2 \text{ billion US dollars} \quad (162)$$

$$\text{Total cost} = 10.2 \text{ billion US dollars} + 8.7 \text{ billion US dollars} + 0.2459 \text{ billion US dollars} = 19.15 \text{ billion US dollars} \quad (163)$$

$$\text{LCOE} = 19,150,000,000 / 182,600,000,000 = 0.105 \text{ \$/kWh, which means 10.5 cents/kWh.} \quad (164)$$

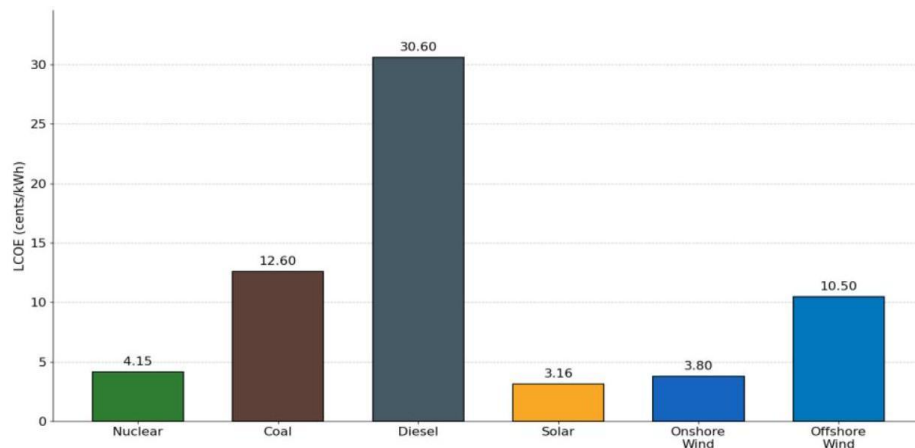


Figure 3.
LCOE comparison between different energy sources.

The cost comparison shows major economic differences between energy sources when producing the same electricity output of 8.3 TWh/year. Although nuclear power has a very high initial construction cost, its fuel requirement is relatively small, leading to lower long-term fuel expenses compared to fossil fuels. Coal and diesel power plants require continuous large-scale fuel consumption, which significantly increases their total lifetime cost and LCOE values. Diesel produced the highest electricity cost among all sources mainly because of fuel expenses, while coal also remained expensive due to both fuel and operational costs. Renewable energy sources such as solar and onshore wind showed relatively low LCOE values because they do not require fuel during operation, although they require large installation areas and high infrastructure deployment. Offshore wind had a higher overall cost because of installation and maintenance difficulties in marine environments. Overall, the results suggest that nuclear energy can provide large-scale continuous electricity generation with competitive long-term costs, while renewable sources offer low operational emissions but require significantly larger infrastructure systems to match the same electricity output.

4.7 Death Rates:

Nuclear: The death rate per TWh is estimated to be only 0.03 (Ritchie, 2020).

$$\begin{aligned} \text{Total deaths} &= \text{death rate per TWh} \times \text{total energy produced} = 0.03 \text{ deaths} \\ &\text{per TWh} \times 8.3 \text{ TWh} = 0.249 \text{ deaths} \end{aligned} \quad (165)$$

Coal: The death rates of coal are high with a 24.62 deaths per TWh (Ritchie, 2020).

$$\text{Total deaths} = 24.62 \text{ deaths per TWh} \times 8.3 \text{ TWh} = 204.346 \text{ deaths} \quad (166)$$

Diesel: Diesel is an oil-based energy source with a death rate of 18.43 deaths per TWh (Ritchie, 2020).

$$\begin{aligned} \text{Total deaths} &= 18.43 \text{ deaths per TWh} \times 8.3 \text{ TWh} = 152.969 \\ &\text{deaths} \approx 153 \text{ deaths} \end{aligned} \quad (167)$$

Solar panels: Solar energy has a death rate of 0.02 deaths per TWh (Ritchie, 2020).

$$\text{Total deaths} = 0.02 \text{ deaths per TWh} \times 8.3 \text{ TWh} = 0.166 \text{ deaths} \quad (168)$$

Wind turbines: Although onshore and offshore wind turbines have different risk profiles, most studies combine them since the datasets are usually drawn from global wind turbines accidents (all turbines, all locations), so the resulting death rate estimate 0.04 deaths per TWh (Ritchie, 2020).

$$\text{Total deaths} = 0.04 \text{ deaths per TWh} \times 8.3 \text{ TWh} = 0.332 \text{ deaths} \quad (169)$$

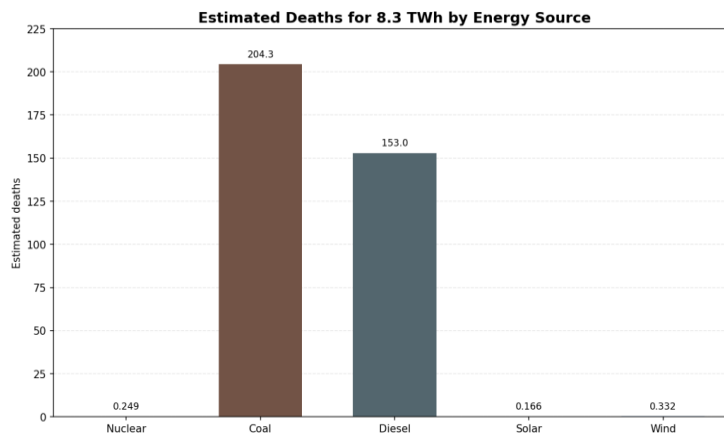


Figure 4.

Comparison of the death rates per year between different energy sources.

Graph 4 shows the safety of nuclear and renewable energy sources compared to fossil fuel. The death-rate comparison shows major differences in the safety impacts of different energy sources. Fossil fuels such as coal and diesel have the highest estimated death rates, mainly due to air pollution, accidents during extraction and transportation, and long-term health effects associated with combustion emissions. Coal produced the highest estimated number of deaths for the same electricity output, followed by diesel. In contrast, nuclear, solar, and wind energy showed extremely low death rates per TWh generated. Although nuclear accidents are often highly publicized, statistical data indicates that nuclear energy remains among the safest large-scale electricity sources when measured per unit of electricity produced. Renewable sources such as solar and wind also demonstrated very low death rates, mainly associated with manufacturing, installation, and maintenance accidents rather than operation itself. Overall, the results suggest that low-carbon energy sources, especially nuclear and renewables, provide significantly safer electricity generation compared to fossil fuels.

This comparison shows that nuclear energy combines a low LCOE, high capacity factor, low CO₂ emissions, and a low death rate, while producing large amounts of electricity from a relatively small area. Renewable sources such as wind and solar also have low emissions and low death rates, but they require significantly more land and infrastructure to match the same energy output due to their lower capacity factors. Onshore and offshore requires hundreds to thousands of turbines, while solar requires millions of panels. In contrast, fossil fuels like coal and diesel have higher LCOE, much higher CO₂ emissions, and higher death rates due to fuel combustion and pollution.

Overall, nuclear energy stands out as a highly efficient and reliable source for largescale electricity generation, while renewable energy remains essential for sustainability and reducing environmental impact.

Radioactive Waste Management:

The use of nuclear energy naturally produces nuclear waste. This waste is divided into three levels of radioactivity: low, intermediate, and high. Approximately 90% of nuclear waste is low level waste, made up of lightly contaminated materials such as tools, gloves, and work clothing. This type of waste contains only about 1% of the total radioactivity. High level waste, which makes up just 3% of the total waste but contains roughly 95% of the radioactivity, and about 7% is intermediate level. This high level waste is mainly spent nuclear fuel from the reactor core (World Nuclear Association, 2026b).

Nuclear fuel is extremely energy dense meaning a very small amount of material can produce a huge amount of electricity. Because of this, the total amount of waste generated is relatively small (World Nuclear Association, 2026b).

The radioactivity from the main components of the waste that can pose health risks will decay to safe levels within a few hundred years, as long as the waste is stored and managed properly. This means nuclear waste is not inherently “dangerous forever” it can be handled safely if modern safety standards are followed (World Nuclear Association, 2026b). Used nuclear fuel is kept in wet or dry storage facilities before recycling or direct disposal. When it is removed from the reactor, the fuel is both hot and highly radioactive, so it is first stored in water to allow it to cool down. It can remain in wet storage for years, or after a long period of cooling the fuel is transferred to dry storage facilities in sealed casks (World Nuclear Association, 2026b).

Keeping the used fuel in temporary storage allows both the heat and radioactivity to decrease, which makes recycling and disposal easier and safer. However, these are not permanent solutions. There are two main long term waste management strategies: recycling (reusing nuclear fuel for decades) and direct disposal, where used fuel is treated as waste and placed permanently in a deep geological repository (World Nuclear Association, 2026b). Recycling involves reprocessing the used fuel to recover usable uranium or plutonium so they can be reused in reactors. Direct disposal is a strategy where the used fuel is treated as waste and placed permanently in a deep geological repository underground. In this approach, the fuel is sealed in metal canisters, placed in tunnels, and surrounded by rock and clay to isolate it from the environment. The fission products (the waste generated during recycling) are also stored in the same repository (World Nuclear Association, 2026b).

$$\begin{aligned} \text{Annual Waste} &= \text{thermal power} \times \text{CF} \times \text{days/year} / \\ \text{burnup} &= 3.03 \text{ GW} \times 0.95 \times 365 \text{ day/year} / \\ 55 \text{ GWd/t (World Nuclear Association. (2026b))} &= 19.1 \text{ metric tons per year} \end{aligned} \quad (170)$$

Burnup = how much energy is extracted from the fuel before it's removed from the reactor.

$$\begin{aligned} \text{Waste over the reactor lifetime} &= \\ 40 \text{ year} \times 19.1 \text{ metric tons per year} &= 764 \text{ metric tons of waste are produced over the} \\ \text{reactor lifetime.} & \end{aligned} \quad (171)$$

As mentioned before, to meet the national 3×1000 MW nuclear reactors are needed.

$$\begin{aligned} \text{Total amount of waste over the lifetime of the reactors} &= \\ 3 \times 764 \text{ metric tons of waste that are produced over the reactor lifetime} &= 2,292 \\ \text{metric tons of waste.} & \end{aligned} \quad (172)$$

The results show that although nuclear energy produces radioactive waste, the total quantity generated is relatively small compared to the large amount of electricity produced. Most nuclear waste is low-level waste with low radioactivity, while high-level waste represents only a very small fraction of the total waste volume. The calculations indicate that powering the entire country with three 1 GWe nuclear reactors for 40 years would produce approximately 2,292 metric tons of high-level waste, which is small compared to the enormous electricity output generated over that period. Modern waste management strategies such as wet storage, dry cask storage, recycling, and deep geological disposal are specifically designed to isolate radioactive materials safely from the environment. Although nuclear waste remains radioactive for long periods of time, its volume is manageable when proper storage and disposal systems are applied. These results suggest that radioactive waste management remains a technical and engineering challenge, but one that can be controlled using established safety methods and long-term disposal strategies.

Note: The following methods and calculations apply to HLW only. LLW is typically sent to land-based disposal immediately following its packaging for long-term management [59]. ILW that contains long-lived radioisotopes is also stored pending disposal in a geological repository [59], and ILW with short-lived radioisotopes is disposed of in near-surface disposal facilities, the same as used for LLW disposal [59]. Nuclear waste remains radioactive for a very long time, which is why long-term geological storage is required.

Siting:

Site selection for nuclear power plants in Lebanon requires the evaluation of several key factors, including water availability for cooling, proximity to load centers to reduce transmission losses, distance from populated areas to minimize risk, accessibility for fuel and personnel transport, and waste management capacity (Rama University. (n.d.)) and seismic and tsunami safety due to Lebanon's location on active fault lines and its coastal geography (International Atomic Energy Agency, 2021). These criteria are essential to ensure both operational efficiency and safety in the Lebanese context.

A detailed site selection analysis for Lebanon is beyond the scope of this study and will be addressed in a subsequent research paper.

Limitations:

This study is based on simplified theoretical assumptions in order to allow a clear physics-based comparison between energy sources. It assumes constant electricity demand, fixed capacity factors, and ideal continuous operation of nuclear reactors. Real-world factors such as political and economic instability, grid inefficiencies, transmission losses, construction delays, and regulatory approval processes are not included. Cost values are taken from generalized international estimates and may vary significantly depending on location, time, and local infrastructure conditions in Lebanon. Therefore, the results should be interpreted as a theoretical comparison of energy systems rather than a full engineering or feasibility assessment. This study focuses only on technical and economic aspects. It does not consider political, security, or geopolitical factors that would be very important in a real Lebanese nuclear project.

5 Conclusion

This study set out to investigate whether nuclear power plants could theoretically resolve Lebanon's chronic electricity crisis and meet the national demand, using a physics-based analytical approach. The results demonstrate that three 1 GWe nuclear reactors could theoretically generate 3 GWe of continuous electrical power, exceeding Lebanon's pre-

crisis demand of approximately 2,740 MW and fully meeting the current estimated demand of 3 GWe.

The comparative analysis further reinforced the case for nuclear energy across multiple dimensions. The efficiency comparison demonstrated that nuclear fuel's extraordinary energy density allows a single reactor to produce 8.3 TWh/year while fissioning only 1.16 metric tons of U-235 (equivalent to about 19.1 metric tons of LEU fuel loaded per year) — still a fraction of the fuel required by coal or diesel plants. The environmental analysis highlighted nuclear energy's minimal carbon footprint over its full lifecycle compared to all other sources examined. The land area comparison showed that nuclear energy is particularly well suited for a geographically small country like Lebanon, requiring only 3.367 km² per reactor. The cost analysis suggests that nuclear energy's LCOE of 4.2 cents/kWh makes it highly competitive on the long term — a critical advantage for a country still recovering from a severe economic and currency collapse. Finally, the death rate comparison challenged the widespread public perception of nuclear energy as inherently dangerous — a perception largely shaped by events such as Chernobyl and Fukushima — by demonstrating that nuclear energy is among the safest electricity sources available.

It is important to acknowledge that this study operates under simplified assumptions, including constant national demand CF of 95%, and the exclusion of transmission losses, political, regulatory, and financial constraints. A full implementation would require comprehensive feasibility studies beyond the scope of this work.

Nevertheless, based on the theoretical physics-based analysis conducted, and within the simplified assumptions of this model, nuclear power represents a viable, clean, efficient, and cost-competitive option worth further study for addressing Lebanon's energy crisis.

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