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NUCLEAR ENERGY FOR SRI LANKA'S DECARBONIZED FUTURE: A SUSTAINABLE ALTERNATIVE TO LIQUEFIED NATURAL GAS DEPENDENCE

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Nuclear Energy for Sri Lanka's Decarbonized Future:

A Sustainable Alternative to Liquefied Natural Gas Dependence

by

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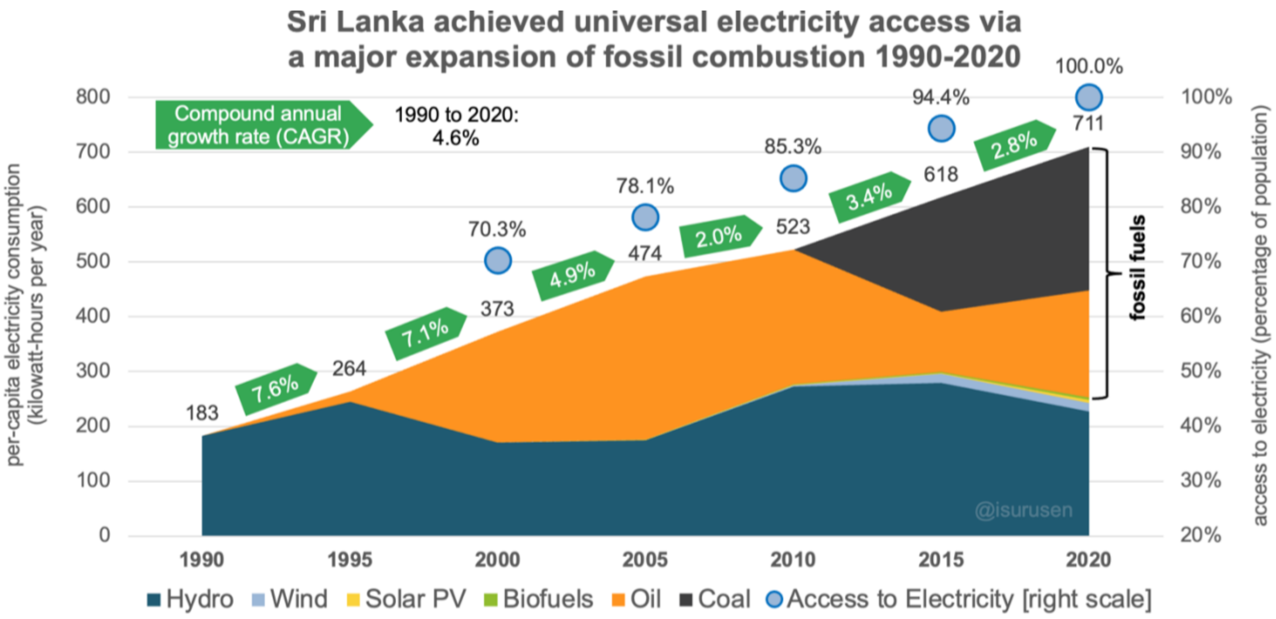
"Energy is part of a historic process, a substitute for the labor of human beings. As human aspirations develop, so does the demand for and use of energy grow and develop."

- David Lilienthal, Atomic Energy: A New Start, 1980

The Democratic Socialist Republic of Sri Lanka is evaluating whether to incorporate nuclear energy to her electricity mix. This research brief evaluates the demands on Sri Lanka's electricity system and considers the relationship between energy consumption and prosperity. Thereafter, it evaluates reliable, affordable, sustainable, and safe electricity provision. Exploring options and barriers for nuclear energy deployment, the report concludes with recommendations for progress.

As the country explores options on-demand energy sources to complement solar and wind generation, limited financial and human resources should prioritize nuclear over liquefied natural gas (LNG), an expensive and price volatile fossil fuel with questionable climate benefits over coal.

2. Country Electricity Profile



Data sources: International Energy Authority (electricity), World Bank (population), Our World in Data (access)

Figure 1: Sri Lanka's electricity consumption and access (IEA, n.d.; Our World in Data, n.d.-a)

Sri Lanka is an island nation with 21.9 million people. After concerted efforts in rural electrification, Sri Lanka celebrated universal electric access in 2016, expanding the associated socio-economic benefits to all her citizens (Asian Development Bank, 2023). From 1990 to 2020, per-capita electricity consumption compounded at an annual rate of 4.6% (Figure 1). Until the mid-1990s, Sri Lanka had largely low-carbon grid, underpinned by hydropower. Per-capita non-fossil electricity generation has not expanded much in the three following decades. By 2018, Sri Lanka's large-scale hydropower potential was largely realized (Asian Development Bank, 2023). Further, the Standardized Power Purchase Agreement for renewable energy plants below 10 megawatts

(MW), promulgated in 1996, catalyzed much run-of-the-river "mini-hydro" development. Sri Lanka's ability further expand hydro is limited (CEB, 2023a). The country relied on the combustion of expensive oil products to expand electricity in the 2000s, and added coal to the mix in 2011. All fossil fuels are imported into the country. In 2019, Sri Lanka's net petroleum import bill of USD 2.4 B equaled 24% of the country's total non-petroleum export income, highlighting fossil fuel's macroeconomic significance (Sri Lanka Sustainable Energy Authority, 2021.

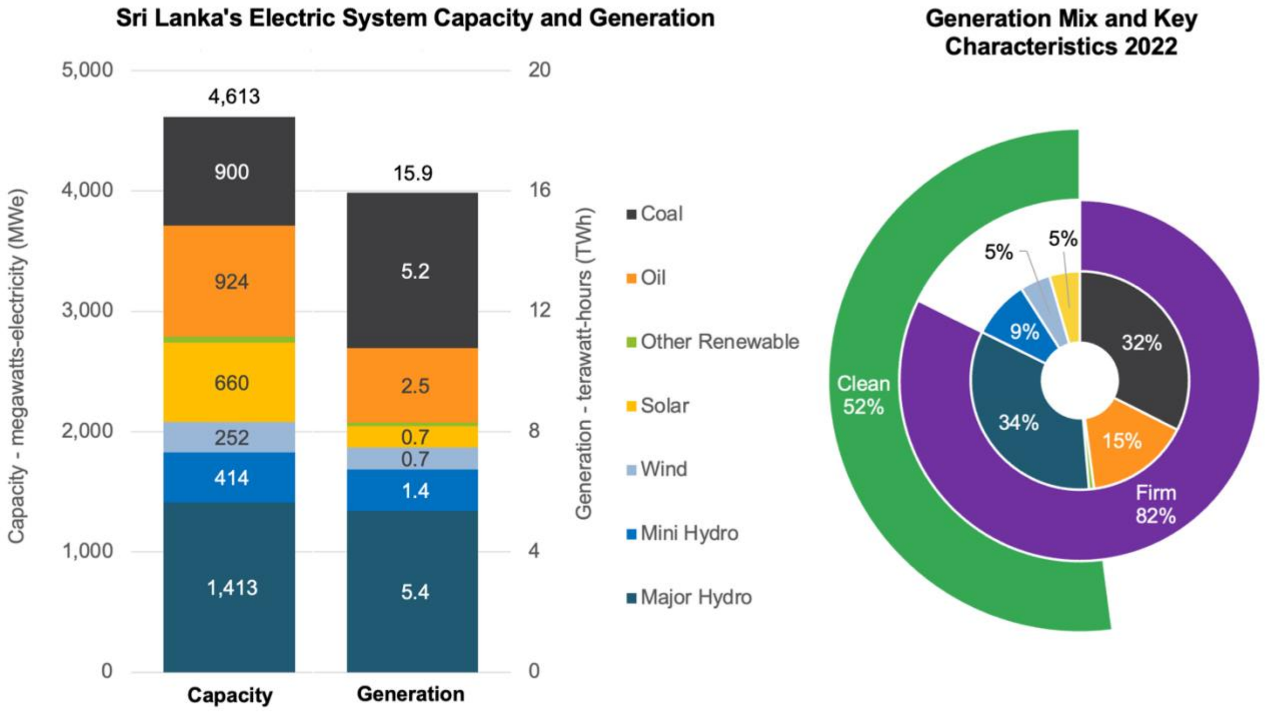
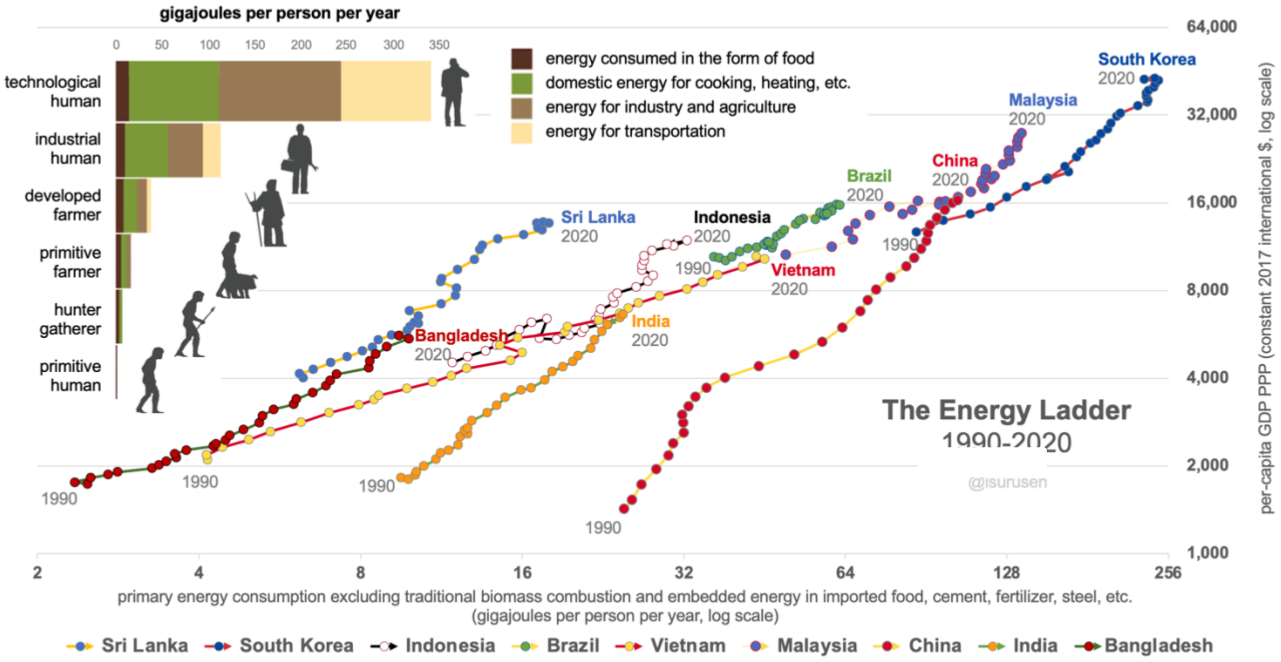


Figure 2: Sri Lanka's electric system capacity, generation, and key characteristics (CEB, 2023b)

In 2022, hydro provided 42% of electric supply, and non-fossil sources totaled 52% (Figure 2). About 18% of Sri Lanka's electricity generation was intermittent – subject to daily or seasonal weather conditions (9% mini-hydro, 5% wind, 3% rooftop solar, 1% grid solar). Firm resources, those able to provide power on-demand regardless of the time of day or weather, made up the rest (34% major hydro, 32% coal, 15% oil, 1% other renewable).

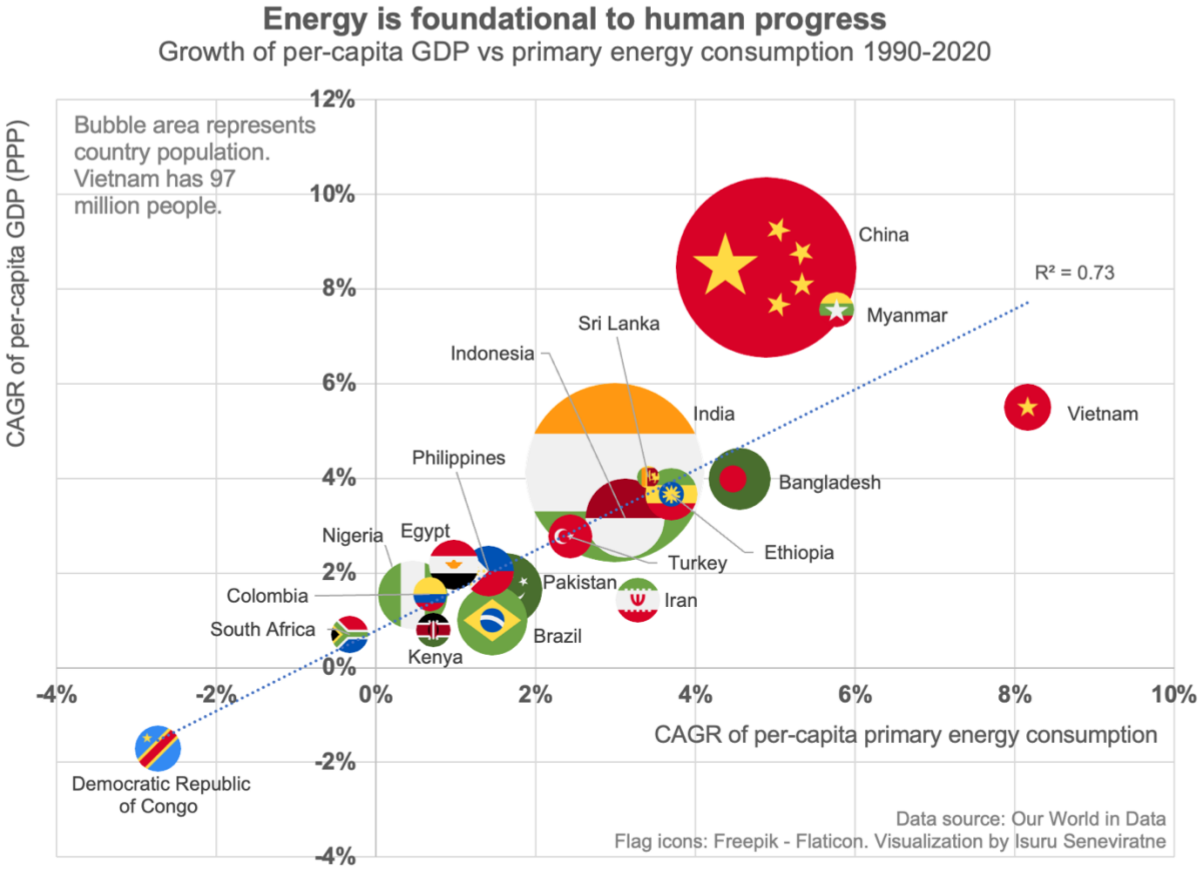
3. The Energy Ladder

Access to modern energy (for electricity, cooking, transportation) is necessary for sustainable development. The UN Sustainable Development Goal 7 calls for "affordable, reliable, sustainable, and modern energy for all" by 2030 (United Nations, n.d.). Studies have shown a positive and significant causal link from energy use to economic growth. Given the strong correlation between Human Development Index and per-capita gross domestic product (GDP) (Our World in Data, n.d.-c), we use GDP as a proxy for human well-being in this brief. Figure 3 visualizes how countries grow their economies along with the key input: energy (Our World in Data, n.d.-b), along with the inset on human progress from The New Net Zero (Maclay, 2014).



Data source is Our World in Data. Inset adopted from The New Net Zero (Maclay, 2014). Visualization by Isuru Seneviratne

Figure 3: The energy ladder: per-capita GDP vs. energy consumption



Data source: Our World in Data
Flag icons: Freepik - Flaticon. Visualization by Isuru Seneviratne

Figure 4: CAGR of per-capita GDP vs. CAGR of primary energy consumption 1990-2020[1]

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[1] When available, energy consumption and GDP for 2020 are used, despite the disparate impacts of the COVID-19 pandemic. 2019 figures are used for Nigeria, Ethiopia, the Democratic Republic of Congo, Myanmar, and Kenya.

Figure 4 demonstrates how the compound annual growth rate (CAGR) of per-capita GDP corresponds to the CAGR of energy consumption from 1990 to 2020 for 18 of the largest emerging economies plus Sri Lanka. Especially at lower levels of consumption, modern energy is key to achieving many socio-economic goals. A World Bank study evaluating cross-country data of more than 60 low-income countries 1985-1999 found that in urban areas, linking households to electricity is the *only* key factor that reduced both infant mortality rate and under-5 mortality rate, and that this effect is *large*, *significant*, and *independent of incomes* (Markandya & Wilkinson, 2007). Expanding household electricity consumption is especially beneficial to women and girls, who are liberated from the drudgery of menial labor (Bryce, 2020).

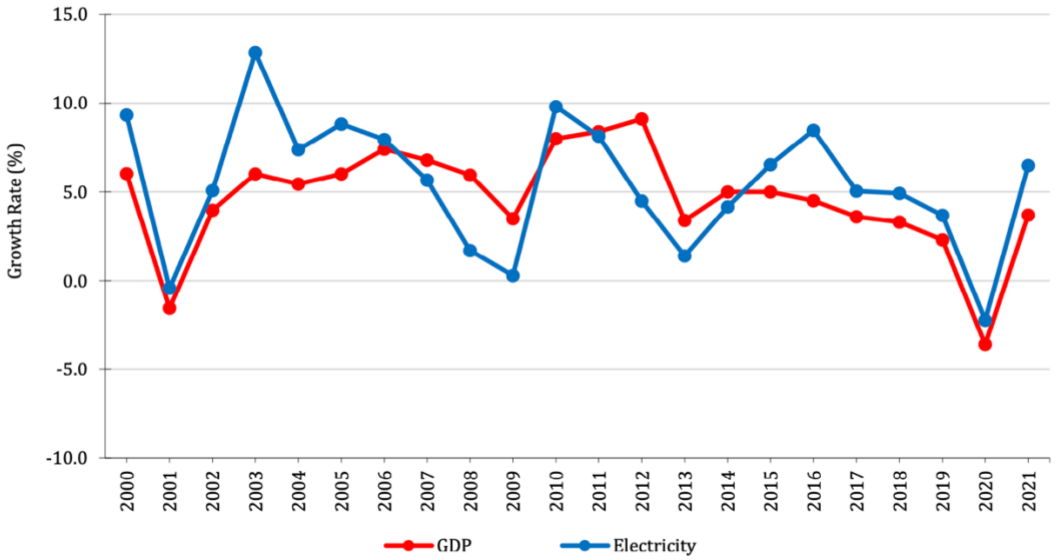


Figure 5: Growth rates of GDP and electricity sales (CEB, 2023a)

Further, higher levels of energy allow new income-generating activities: "productive use of energy" versus "consumptive use" (Brew-Hammond & Kemausuor, 2009). The Asian Development Bank (2023) found that a 1% increase in electricity demand in Sri Lanka *will lead to* a 0.63% increase in per-capita GDP. Figure 5 shows historic growth rates of GDP and electricity sales. While the per-capita electricity consumption in Sri Lanka multiplied ten-fold between 1970 and 2015, average household electricity consumption grew only 43% in this period, showing how commercial and industrial activities proliferated with electricity (Asian Development Bank, 2023). Energy abundance, not scarcity, is a necessary (albeit insufficient) condition to enable emancipatory development (Byrne et al., 1998). For example, with increasing heat waves, so does the need for affordable air conditioning and refrigeration to counter heat stress (Rodrigo, 2023).

Keen to move up the technology value chain, Sri Lanka has identified the Information Technology and Business Process Management (outsourcing) sector as a key plank of her economic future (Sri Lanka Export Development Bank, n.d.). The sector generated USD 1 B of export revenue in 2020, triple the 2015 level. The country had sought to multiply her IT-BPM revenue to USD 5 B by 2025 (International Trade Administration, 2022). The grid operator Ceylon Electricity Board's latest Long-Term Generation Expansion Plan (LTGEP) anticipates that demand growth to compound annually at the rate of 5.2% between 2023 and 2043, an acceleration from the annual growth rate of 4.4% during the previous 15 years (CEB, 2023a).

Electric system reliability is paramount to serve the outsourcing industry. However, severe fiscal mismanagement, exacerbated by pandemic-related shuttering of the tourism industry, drove Sri Lanka into an economic collapse and a humanitarian crisis in 2022 (IMF, 2023). The country ran out of hard currency to import coal for power plants as well as fossil fuels for cooking and transportation (Shukla, 2023). As Sri Lanka is attempting to stabilize the economy with the support of the IMF, lifetime needs for foreign exchange is a key energy security consideration.

4. Climate Action and Nuclear Power

In 2021, Sri Lanka pledged to achieve carbon neutrality by 2050 (Ministry of Environment, 2021). All the scenarios evaluated by CEB in LTGEP have no coal fired plant additions, but the report highlights the need for firm generation sources.

Prompted by the energy crisis and the growing realization that rolling blackouts are harmful to the economy, Sri Lanka is considering nuclear energy. The International Atomic Energy Agency (IAEA) offers Integrated Nuclear Infrastructure Review missions to evaluate the status of countries' civilian nuclear infrastructure development, building on member states' self-evaluation. Phase 1 of such a mission – conducted in April 2022 – concluded that Sri Lanka has engaged the appropriate stakeholders to consider the introduction of nuclear power and has initiated studies to enable the government to make a future decision on the nuclear power program (IAEA, 2022).

Many emerging economies are accelerating their plans to build nuclear power (Ahn et al., 2022). Bangladesh is building two reactors (Paul, 2023; World Nuclear Association, 2023b), Egypt is embarking on a third (Power Technology, 2023; World Nuclear Association, 2023a; World Nuclear News, 2023b), Turkey is powering up the first of four reactors (Burge, 2023; World Nuclear Association, 2023d) – all of Russian origin. The United Arab Emirates is bringing online the fourth reactor of South Korean design (Gulf Business, 2023; World Nuclear Association, 2023e).

Table 1 summarizes the growing electricity needs in the emerging economies building nuclear power plants (Energy Institute, 2023) and a few key characteristics of these deployments. All projects initiated in the 2010s, are coming online in the 2020s. All countries are looking to expand local high-quality jobs and supply chains as the in-country expertise develops. Russian deployments handle the entire fuel cycle, from uranium supply to spent fuel (waste) disposal.

Country	Bangladesh	Turkey	Egypt	UAE
Country electricity generation 2022 Terawatt-hours (TWh)	97.5	326.2	200.8	154.7
10-year electricity generation CAGR	7.2%	3.1%	2.1%	3.8%
Nuclear plants operable or under construction	Rooppur 1&2	Akkuyu 1-4	El Dabaa 1&2 (of 4 planned)	Barakah 1-4
Capacity Megawatts-electric (MWe) [O]perable or [U]nder Construction	2,160 [U]	4,800 [U]	2,200 [U]	4,011 [O] 1,310 [U]
Expected annual output (TWh)	17.0	35.0	17.3	42.0
Construction start	2017 & 2018	2018-22	2022	2012-15
Operational (expected)	2024 & 2025	2023-26	2026-30	2020-23
Reactor design	VVER-1200/V-523	VVER-1200/V-509	VVER-1200/V-529	APR-1400
Vendor	Rosatom	Rosatom	Rosatom	Korea Electric Power Co (KEPCO)
Capital investment	USD 12.6 B (2015 est)	USD 20 B (2022 est)	USD 15 B	USD 24.4 B (2016 est)
Capital cost intensity (USD per watt)	5.9	4.2	6.8	4.6
Initial key funding sources	90% Russian loan	Build-Own-Operate model	85% Russian loan	Debt: USD 16.2 B Abu Dhabi + USD 2.5 B South Korea Equity: 18% KEPCO
Interest rate	LIBOR plus 1.75%, capped at 4%		3%	tbd
Loan term	28y, after 10y grace period	51%+ of equity	22y	Korean debt: 18y
Local content share	~1,500 Bangladeshis trained in Russia	400 Turkish companies in the supply chain	20% for the 1st plant, increasing thereafter	Transitioning to local expertise in time
Fuel supply and waste disposal	Russia	Agreed fuel fabrication plant	10y Russian contract for plant operation and fuel cycle	EDF (France), national site or "take-back"

Table 1: Key characteristics of emerging market new nuclear deployments

4.1. Effective

Figure 6: The energy trilemma: affordable, reliable, and sustainable (Powerstar, 2022)

An electric system has to balance three main competing objectives: reliability, affordability, and sustainability, in a challenge known as the *energy trilemma* (Figure 6). As Sri Lanka embarks on prioritizing the climate objective (the sustainability dimension), it behooves the country to evaluate other jurisdictions that have actually achieved deep decarbonization while ensuring reliable and affordable energy. See Appendix A for country energy and emission profiles.

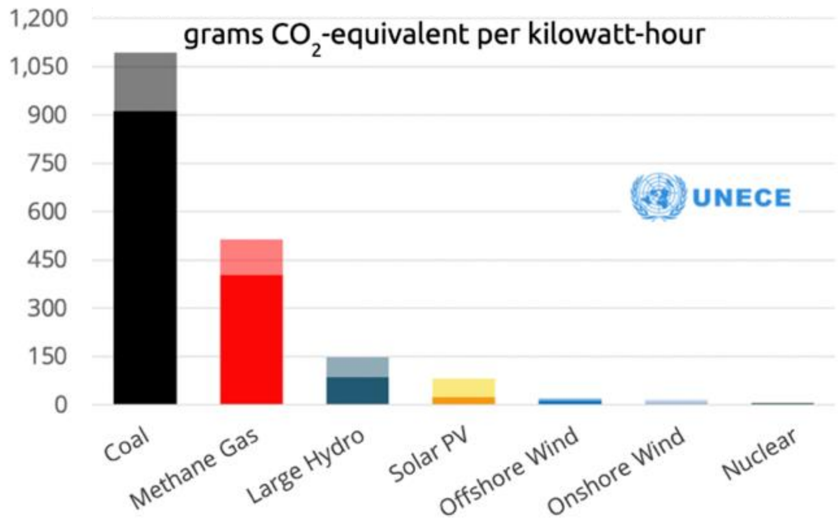
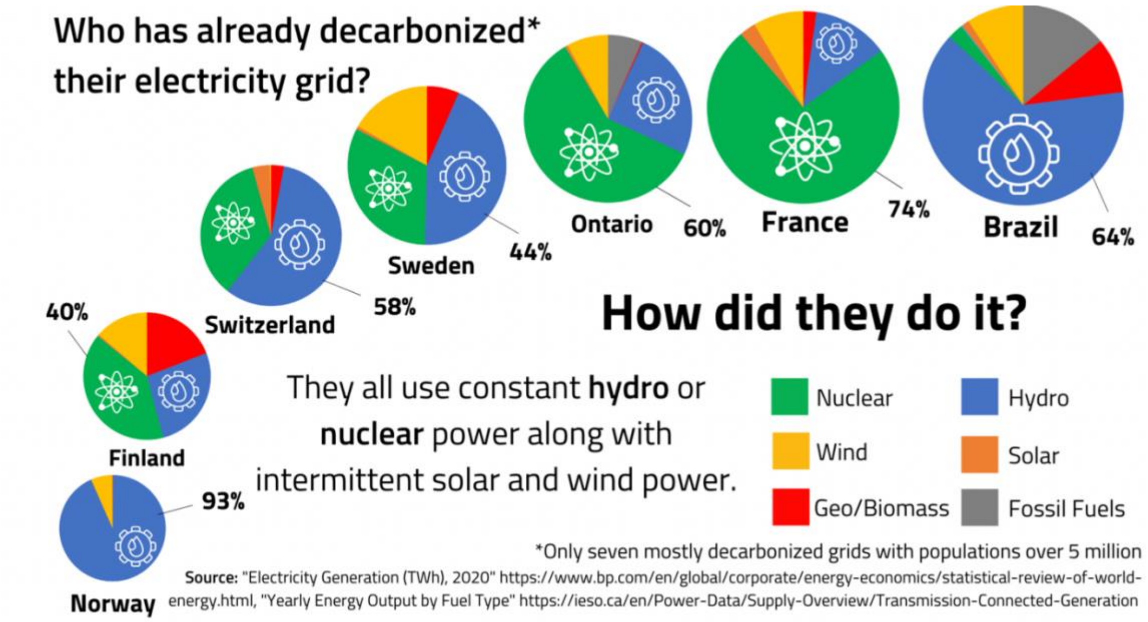


Figure 7: Life-cycle greenhouse gas emissions by technology (United Nations ECE, 2021)

According to a comprehensive United Nations analysis (Figure 7), nuclear power has the lowest cradle-to-grade greenhouse gas emissions intensity per unit of electricity generated (grams carbon-dioxide CO_2-equivalent per kilowatt-hour, kWh).

Figure 8 shows that countries that have achieved deep decarbonization have done so with the expansion of hydropower and nuclear energy (Generation Atomic, 2021; Sepulveda, n.d.).



*Only seven mostly decarbonized grids with populations over 5 million

Source: "Electricity Generation (TWh), 2020" https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html, "Yearly Energy Output by Fuel Type" https://ieso.ca/en/Power-Data/Supply-Overview/Transmission-Connected-Generation

Figure 8: Decarbonized electric grids serving over 5 million people (Generation Atomic, 2021)

Jurisdictions that invested heavily in solar and wind energy suffer from energy scarcity and high prices (Peters, 2022). Germany, the global industrial leader, is to invest over half a trillion Euros in *energiewende* "energy turnaround" between 2000 and 2025 (Düsseldorfer Instituts für Wettbewerbsökonomik, 2016). This program promotes solar, wind, and energy storage, while shutting down nuclear power, driven by fears (David-Wilp, 2022). The resultant high energy prices are a key driver of the country's recent rapid deindustrialization (Wilkes & Randow, 2023), all while causing avoidable greenhouse gas emissions (Knopf et al., 2014; Partanen, 2021).

Heeding similar unscientific advice, Sri Lanka instated an overnight chemical fertilizer ban that caused farmers to lose 54% of their crop yields via a 81% increase in weed infestation, a 73% increase in insect infestation, and a 77% increase in disease infestation (Kynetec, 2022). Sri Lanka does not have the luxury of a developed nation to weather the consequences of embarking on an energy transition with technologies that have not been tested at scale (Temple, 2018). Sri Lanka must make her energy choices based on real-world evidence.

The fastest 10-year national deployments of low-carbon electricity on a per-capita basis have been with hydro and nuclear (Figure 9). This visualization by Grant Chalmers uses the methodology developed by Cao et al. (2016) and the latest Statistical Review of Energy (Energy Institute, 2023).

Nuclear plants can be built on-time and on-budget, as has been done across the world. Recent Western first-of-a-kind developments have taken too long and cost too much. Much like with any manufacturing processes or infrastructure projects, repeated deployment of the same module help mature supply chains and realize optimizations (U.S. Dept of Energy, 2023). Thus, were Sri Lanka to embark on developing nuclear power plants, it should choose a proven reactor type from an experienced vendor. See §5 for more detail.

Below we consider how nuclear fares along the dimensions of reliability, affordability, sustainability, and safety.

4.2. Reliable

Asian Development Bank (2023) stressed that any form of power interruption and rationing of electricity consumption may cause an adverse effect on Sri Lanka's economic growth. Unlike most commodities, electricity is a service that requires absolute moment-to-moment continuity in power supply in-line with demand. In all electric grids, firm clean generation sources are necessary to ensure grid reliability (U.S. Dept of Energy, 2023).

Fuel-based generators can operate for as long as the on-site fuel lasts. Current nuclear plants have 18-24 month refueling cycles, while some advanced reactors could last 10 years without fresh fuel. With long refueling cycles and low fuel costs, nuclear ensures energy security. Fuel-less systems that harvest wind and solar are dependent on weather conditions to function. The quantum of storage required accelerates rapidly at higher penetration levels intermittent generation (Figure 10). Grid-scale storage beyond a few hours remains extremely expensive (Temple, 2018). Thus, intermittent resources require firm backup generation.

This study does not evaluate dendro, the combustion of biomass for power generation, although it is a firm clean resource if sustainably harvested (Sugathapala, 2021).

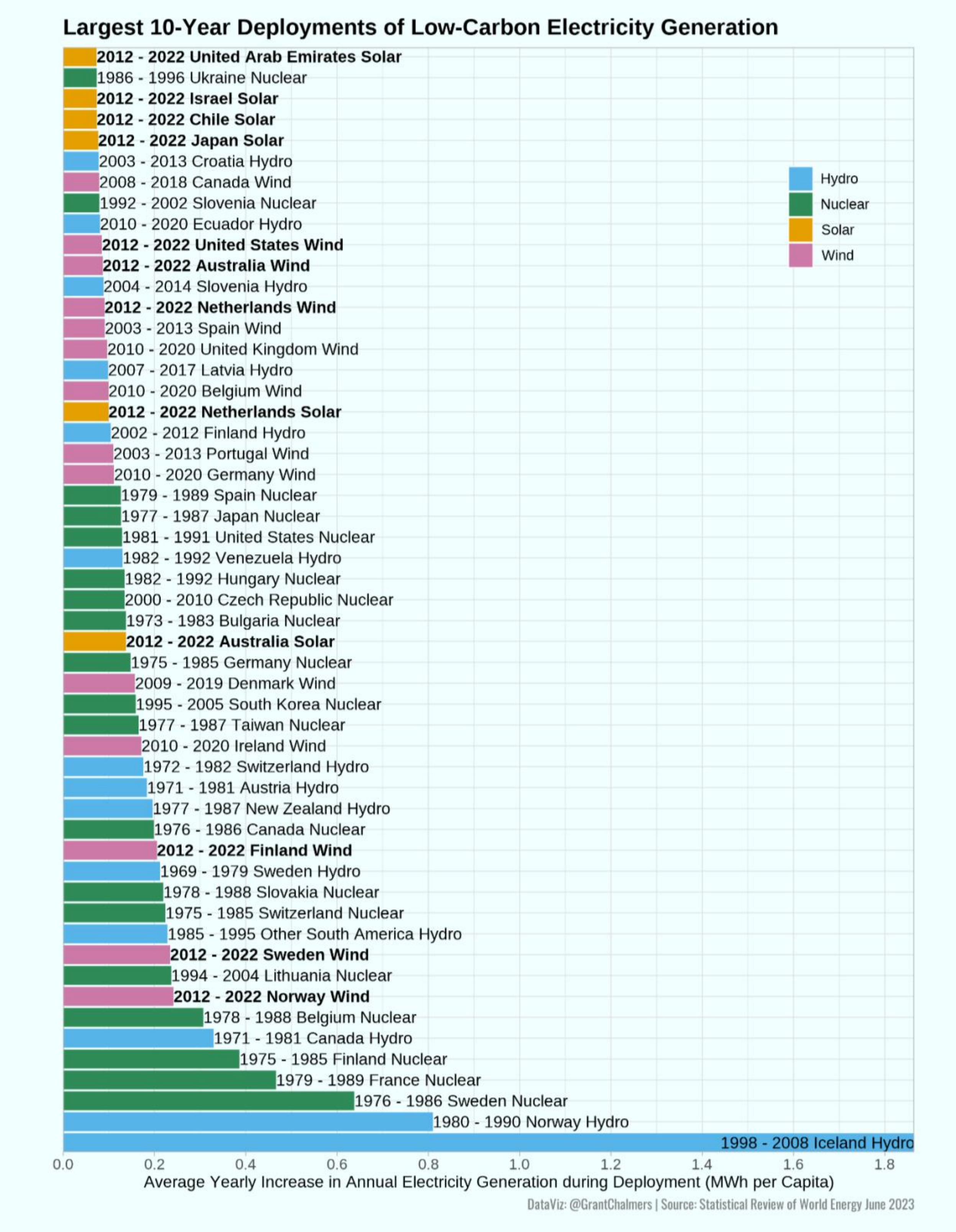


Figure 9: Fastest 10-year deployments of low-carbon electricity generation

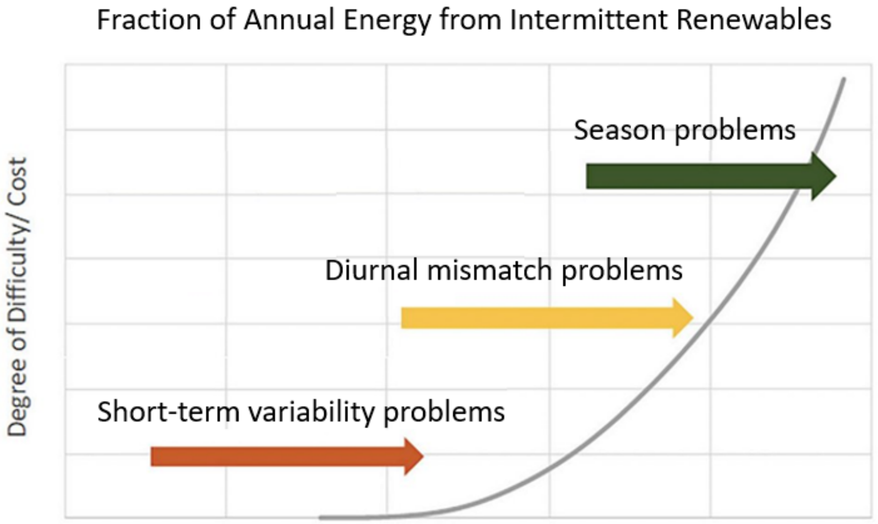


Figure 10: The degree of difficulty and cost of integrating intermittent energy along with penetration levels (Denholm et al., 2021)

LTGEP shows a heavy dependence on methane gas ("natural gas") combustion to realize the "70% renewables by 2030" mandate set by the government. With no developed domestic gas source, Sri Lanka would need major investments in LNG infrastructure for this option. LNG is a fossil fuel formed by chilling gas to -127 °C (-260 °F). Liquefaction reduces the volume by 600x, allowing the product to be shipped across oceans. At the receiving port, the liquid is converted back into a gas before piping to a power plant for combustion. The investment in gas-based power plants would be on top of the regasification, pipeline, and storage infrastructure. Liquefaction, storage at sea, and regasification all consume energy, known as parasitical load.

4.3. Affordable

CEB's mandate is to "develop and maintain an efficient, coordinated and economical system of electricity supply for the whole of Sri Lanka" (CEB, 2023a). Affordable electricity is essential not only to convert "consumptive uses" like air conditioning from luxuries into plenitude, but also to ensure Sri Lankan goods and services are competitive at the world stage.

The LTGEP identifies a few of the large-scale development projects expected to drive electricity demand:

a) Colombo Port City Development (393 MW demand by 2040),

b) Western Region Light Rail Transit Project (135 MW demand by 2039),

c) Solid Waste Management Project, and

d) Metro Colombo Urban Development Project.

A systematic framework is required to compare the costs of providing on-demand electricity from various generation sources (Figure 11). The system has plant-level costs, grid-level costs, plus social and environmental costs.

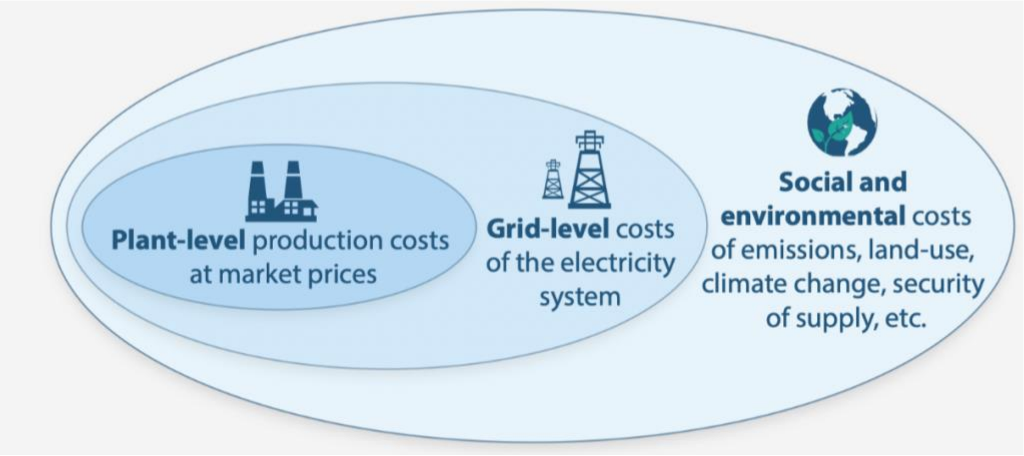


Figure 11: System-level costs of electricity provision (NEA, 2022)

Plant-level costs of solar and wind have come down in the last two decades, and Sri Lanka should look to expand these resources, especially solar. However, jurisdictions that greatly expanded these intermittent resources have seen a disproportionate rise in grid-level costs of electricity (Sepulveda, n.d.), leading to increasing inequity in some jurisdictions like California (Perry et al., 2021). The need for storage and transmission rise significantly at higher penetration levels (Denholm et al., 2021; Hirth, 2013; Idel, 2022; U.S. Dept of Energy, 2023). Battery energy storage systems wear out with usage, which necessitate replacement every 10 years or so (CEB, 2023a). The ratepayer and taxpayer ultimately foot the bill on the electricity system, even when service is degraded through unfortunate policy choices (Angwin, 2020). Even excluding storage needs beyond 2030, Sri Lanka's LTGEP shows how increasing renewables beyond 60% of the grid raises costs substantially.[2] Most technology-inclusive cost-optimized deep decarbonization models for the U.S. require a major expansion of nuclear energy (Clack et al., 2022; Kim, 2023; Larson et al., 2021; Stein et al., 2022; U.S. Dept of Energy, 2023).

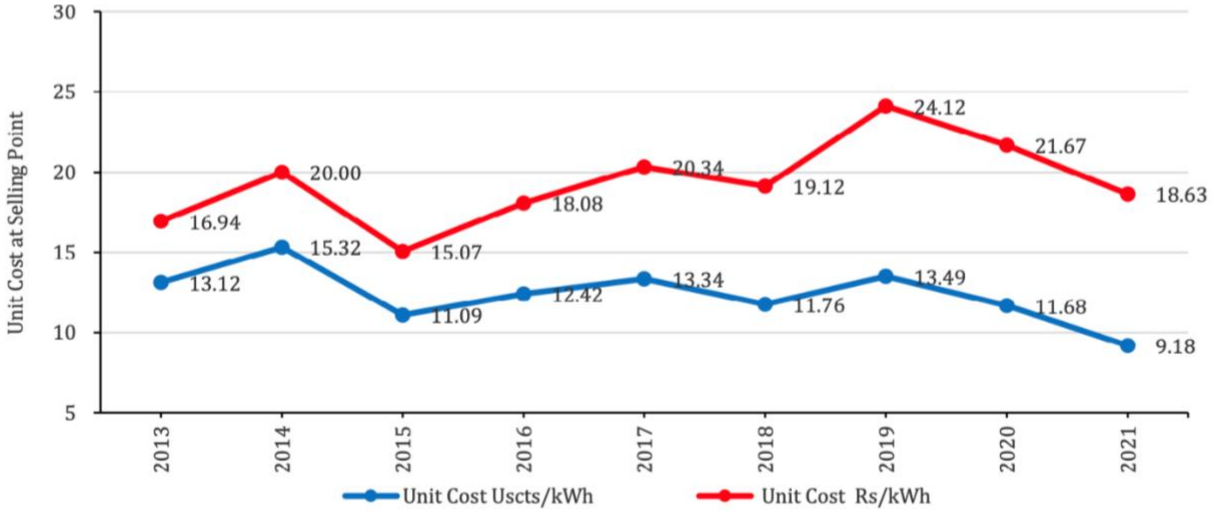


Figure 12: Sri Lanka's unit cost of electricity (at selling point) (CEB, 2023a)

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[2] Note that 34% of Sri Lanka's 2022 electricity came from (largely on-demand) major hydro (Figure 2), demonstrating the challenge of integrating even relatively low levels of intermittent renewables.

The evolution of Sri Lankan electricity costs is graphed in Figure 12. A government-owned regulated monopoly, CEB has not been able to cover all its expenses in recent years (CEB, 2023b).

Electricity transmission and distribution losses were reduced from 21.4% in 2000 to 9.5% in 2021, which likely helped bring delivered costs down. However, there is limited potential to economically wring out further efficiencies (CEB, 2023a).

Table 2 compares key cost components of electricity generation technologies, summarizing findings from CEB (2023b, 2023a) and other sources. While nuclear plants have higher upfront capital costs, their design life is 2-4x that of other generation sources. With minimal fuel needs, nuclear operating costs do not fluctuate with global fossil fuel prices. LNG prices in Asia have been tied to the price of oil imported into Japan.

Another area that nuclear outcompetes other technologies is the capacity factor, the percentage of time that a power plant generates at the maximum output level. Some technologies, like solar and wind, are inherently limited by time or weather conditions. Situated in the Indian Ocean, Sri Lanka has two monsoon seasons, which impact wind and hydro availability. With a capacity factor range of 80-90%, nuclear plants are the most reliable energy source.

Electricity Technology	Coal	Oil (Diesel)	Gas (LNG)	Hydro	Nuclear	Solar	Onshore Wind	Offshore Wind
Design life (years)	30	20	20-30	100	40-80	25	25	25
Capacity factor (global, projected)	70%	44%	65%	varies	85%	20%	35%	45%
Capacity factor (Sri Lanka, 2022)	66%	30%	n/a	42%	n/a	17%	33%	n/a
Capital cost intensity (USD per watt), including 10% interest during construction	1.9-2.0	1.1	0.4-1.1 (excluding regasification, storage, pipeline infrastructure)	tbd	6.1	tbd	tbd	tbd
Cost per unit generation at 80% capacity factor (US cents per kWh)	7.90-8.10	11.80	8.60-12.50	tbd	9.50	tbd	tbd	tbd
Fuel consumed (grams per megawatt-hour)	300,000	194,800	112,000	-	3	-	-	-
Fuel cost in Sri Lanka (USD per megawatt-hour)	71 @ USD 140/ton	290 @ USD 0.96/litre	104 @ USD 13.6/million BTU	-	6.3 (2021 U.S. average)	-	-	-

Table 2: Electricity generation technology cost components

The available funding options is a major factor in choosing electricity generation technologies. See §6.1 for a discussion on financing nuclear power plants.

4.4. Sustainable

In January 2022, the Public Utilities Commission of Sri Lanka issued the guidelines to achieve 70% electricity energy generation through renewable sources by 2030, to build no new coal plants, while reaching Carbon Neutrality in 2050. While Figure 7 visualizes climate impact of various electricity generation sources, this section evaluates other sustainability dimensions.

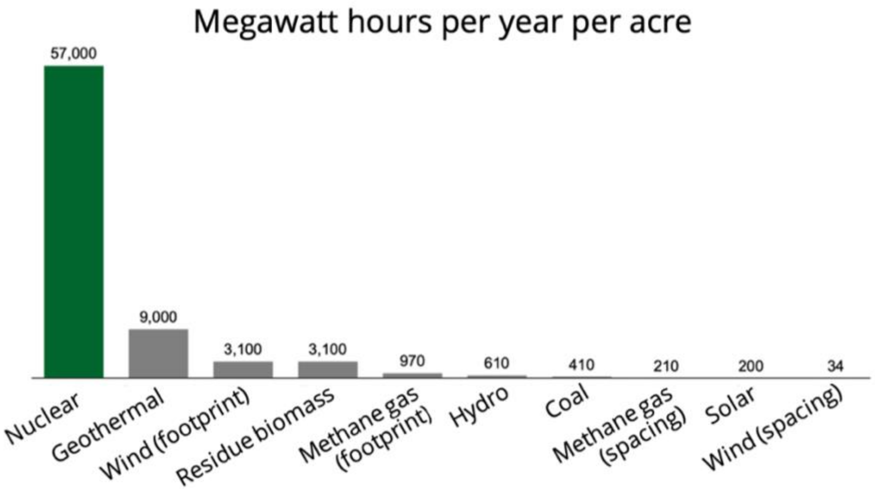
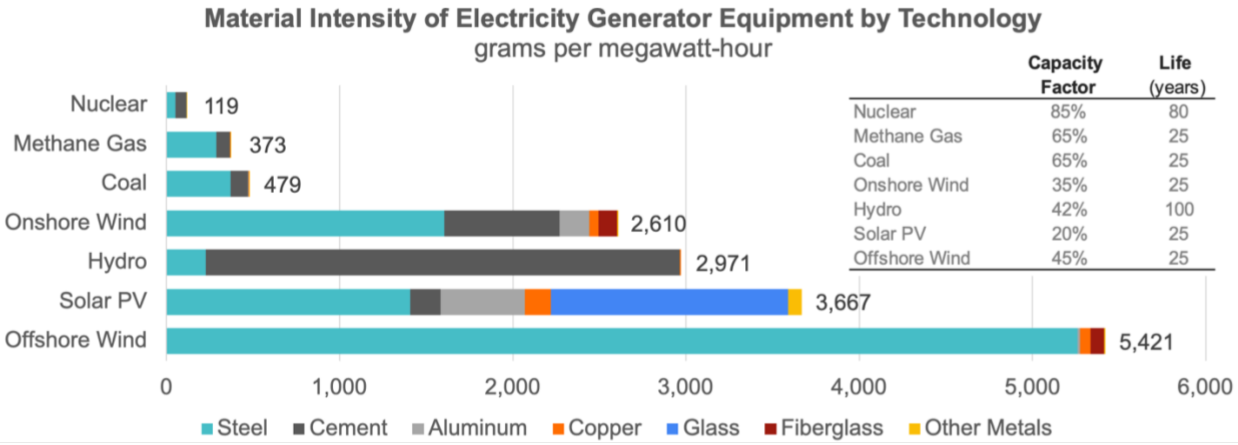


Figure 13: Land productivity of electricity generation technology (U.S. Dept of Energy, 2023)

Industrial energy systems’ land use footprint is proportional to habitat destruction and biodiversity loss. Figure 13 demonstrates the life-cycle land productivity of various electricity generation technologies. Nuclear’s energy density is orders of magnitude higher than other low-carbon energy sources. Using a mere fraction of the space needed allows nuclear energy to liberate both humanity and nature (Katz, 2002).

Another sustainability factor is the material needed for energy generation. Extracting the necessary resources (as equipment or fuel) has ecosystem and human health impacts. Figure 14 has the equipment requirements divided by total expected generation (based on capacity factor and design life) while Figure 15 includes fuel needs. Equipment needs are averages from the survey by Wang et al. (2023) and the fuel mass is based on Touran (2023), adjusted for the uranium enrichment multiplier for nuclear fuel (World Nuclear Association, 2022).



	Capacity Factor	Life (years)
Nuclear	85%	80
Methane Gas	65%	25
Coal	65%	25
Onshore Wind	35%	25
Hydro	42%	100
Solar PV	20%	25
Offshore Wind	45%	25

Figure 14: Equipment material intensity by electric technology

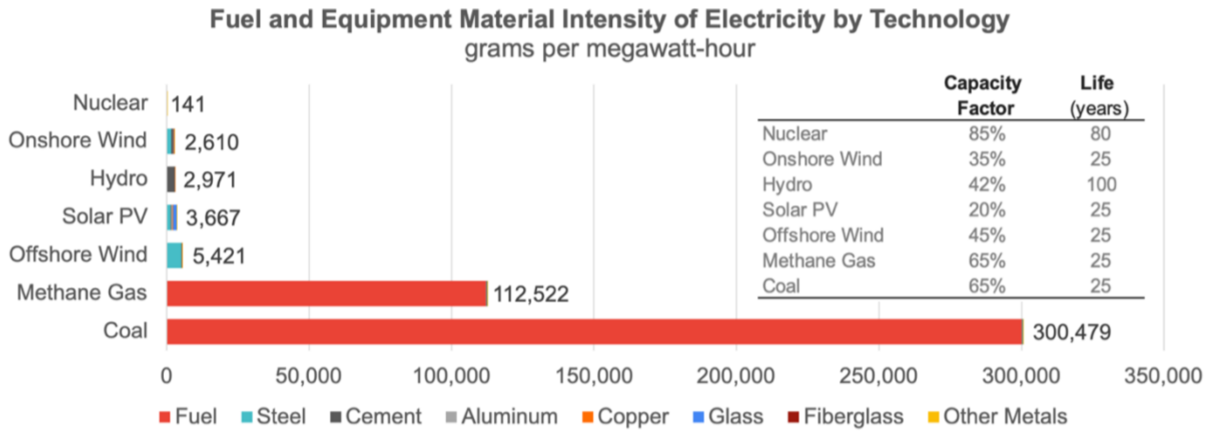
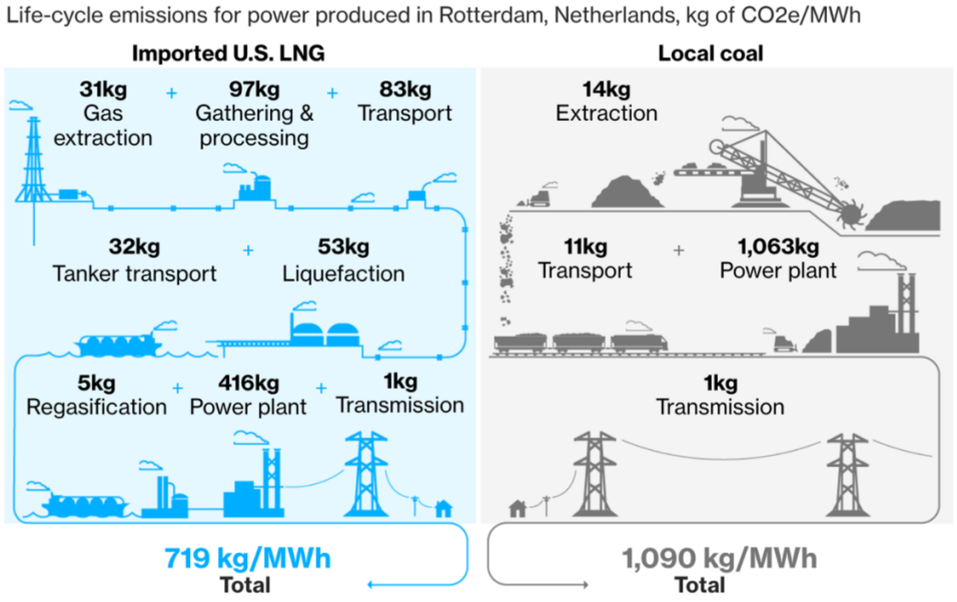


Figure 15: Equipment plus fuel material intensity by electric technology

While electricity from gas combustion has half the carbon dioxide emissions of coal power (IPCC, 2014), the impact of methane leaks may negate much of the climate gains (Gordon et al., 2023; Howarth, 2019). Methane is a greenhouse gas with the global warming potential 34x that of CO_2 on a 100-year time horizon and 86x that of CO_2 over a 20-year horizon (IPCC, 2013). Beyond needing energy input, every step of the methane gas supply chain is susceptible to leakage. Figure 16 compares the life-cycle greenhouse gas impact (using 20-year global warming potential) of burning imported U.S. LNG vs. local coal in Rotterdam, Netherlands.



Source: Department of Energy

Figure 16: Life-cycle emissions of European power using U.S. LNG vs. local coal (Traywick et al., 2020)

4.5. Safe

Safety is a key consideration as well. Over six decades of operational data from tens of countries around the world have shown that nuclear energy is as safe as any renewable energy source (Figure 17), despite contrary claims by opponents like Byrne et al. (1988). While most casual observers can name the three largest nuclear accidents in its history, upon reflection we realize that only one of them caused human deaths.

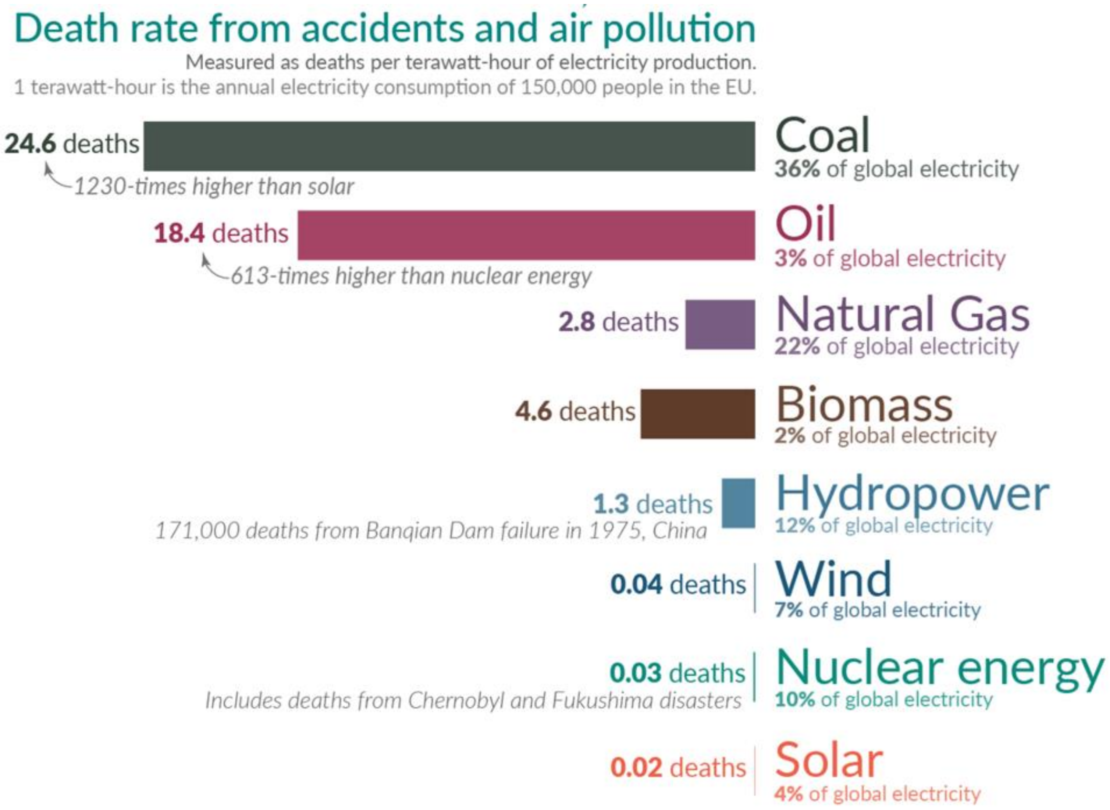


Figure 17: Death rate by electricity generation technologies (Our World in Data, 2020)

1) The 1986 Chernobyl nuclear reactor in the former Soviet Union was abused into an accident, estimated to cost the lives of 300-500 unprotected emergency personnel and children from thyroid cancer (UNSCEAR, 2011). The bigger failure was the government cover-up effort that allowed the largest uncontrolled radioactive release into the environment from any civilian nuclear operation.

2) The Fukushima nuclear plant accident, in Japan 2011, stalled the revival of the second age of nuclear power and prompted Germany to entirely phase out the technology (Goldstein & Qvist, 2019). Despite being the second largest civilian nuclear accident, on a probability-weighted basis, this incident may cause at most one radiation-related death (UNSCEAR, 2014), when nearly 20,000 lives were lost due to the earthquake and tsunami.

3) No civilian was harmed at the 1979 Three Mile Island nuclear accident in the U.S. (UNSCEAR, 2011).

In most cases, public perceptions are formed based on hazards, not actual risks (Juma, 2016). In determining what investments constitute as sustainable, European Union’s highest scientific body, Joint Research Centre, found “no science-based evidence that nuclear energy does more harm to human health or to the environment than other... climate change mitigation [technologies]” (EU SCHEER, 2021).

The next section will evaluate nuclear energy options for Sri Lanka.

5. Nuclear Power Options

A major challenge for a country like Sri Lanka is the size of the electric grid vs. the output of a large nuclear plant. Including rooftop solar, Sri Lanka's total installed power capacity of 4,613 MWe generated 15.9 TWh in 2022 (Figure 2). Prudent planning would prevent any single generating unit be larger than 10–15% of grid capacity. LTGEP expects the 2040 peak electric demand to reach 7,100 MW, more than double the 2022 level. Even then, CEB deemed that the grid would find it difficult to accommodate a nuclear plant larger than 600 MW (CEB, 2023a).

Reactor	Developer	Country	Floating	Power MWe	Design Life (years)	Refuel Cycle (years)	Deployment	Constr. Start	Comm'l Operation (expt)
CNP-300	CNNC	China	land	315	40	1	Qinshan, Zhejiang Province, China	1985	1991
KLT-40S	Rosatom	Russia	floating	35	40	2.3	Akademik Lomonosov, Russia	April 2007	May 2020
ACP100	CNNC and NPIC	China	land	125	60	2	Changjiang, Hainan Province, China	July 2021	(end 2026)
BWRX-300	GE Hitachi	U.S.	land	300	60	?	Darlington, Ontrario, Canada	(end 2024)	(2028)
PWR-20	Last Energy	U.S.	land	20	42	6 (replace-ment)	Legnica Special Economic Zone, Dolnośląskie, Poland	(2024)	(2026)
VOYGR	NuScale Power	U.S.	land	77	60	2	Carbon Free Power Project, Idaho, U.S.	(Dec 2025)	(end 2029)
IPHWR-220	NPCIL	India	land	236	40	2	Madras Atomic Power Station, India	1970	1984
RITM-200N	Rosatom	Russia	land	55	60	6	Ust-Kuyga, Yakutia Republic, Russia		
ACPR-50S	CGN	China	floating	60	40	2.5	(CNOOC oil platform?)		
SMR-160	Holtec International	U.S.	land	160	80	3.5	(Potential: Oyster Creek, NJ, U.S.; Temelin, Czech Rep; Rovno, Ukraine)		
Rolls-Royce SMR	Rolls-Royce SMR Ltd	U.K.	land	470	60	1.5-2	(4 potential U.K. sites identified in 2022)		
SMART	KAERI	South Korea	land	100	60	3	(King Abdullah City for Atomic and Renewable Energy, Saudi Arabia)		
NUWARD	EDF	France	land	170	60	2		(2030)	

Table 3: Smaller reactor options for small grids

The growing set of Small Modular Reactor (SMR) offerings may be more apt for Sri Lanka than the large reactors deployed in Bangladesh, Turkey, Egypt, and the UAE. SMRs incorporate features such as load following, extended refueling intervals, applicability for other uses, and passive safety. SMRs hold the promise of converting nuclear plant deployments from large infrastructure projects to factory-manufactured products. This shift aims to significantly reduce project risks, shorten deployment timescales, and lower costs. These units can be deployed as one-off, or combined into sets, based on demand.

Table 3 samples smaller conventional reactor options and emerging SMRs. The options were selected on the potential to deploy in the 2030s, based on licensing, supply chain, financing, fuel type, and other factors identified in OECD NEA's Small Modular Reactor Dashboard (2023b, 2023a). Only thermal reactors utilizing uranium (UO_2) pellets were considered, excluding fast reactors and those with novel or uncommon fuel types (molten salt, TRISO, metallic U-Zr alloy).

- **CNP-300** is a proven reactor type that Chinese National Nuclear Corporation (CNNC) has deployed abroad at the Chashma Nuclear Plant in Pakistan. Four reactors entered commercial operation at Chashma in 2000, 2011, 2016, and 2017, with another planned. The Export-Import Bank of China (CHEXIM) provided USD 1.5 B of 20-year debt to support the construction of the third and fourth of these plants at a 3.1% blended interest rate (Bowen, 2022).

- **KLT-40S** is Russia's first floating nuclear power plant design, developed by Rosatom, Russia's State Atomic Energy Corporation. The *Akademik Lomonosov*, with two KLT-40S units, entered commercial operation in May 2020 (OECD-NEA, 2023a). Docked at the city of *Pevek*, this plant provides electricity and heat to the remote regional grid.

- **ACP100** (Linglong One) is China's first land-based SMR built for electricity production, heating, steam production or seawater desalination (Xu, 2016). Construction of the first demonstration ACP100 reactor began in 2021 at the Changjiang nuclear power site. Identified as a 'key project' within China's 12th Five Year Plan, such power plants are to combine two to six reactors (World Nuclear News, 2021).

- Established in 2007, GE Hitachi is a nuclear alliance created by the American and Japanese multinational conglomerates General Electric and Hitachi. **BWRX-300** is the tenth iteration of the BWR reactor model. The first BWRX-300 deployment, slated at the Darlington nuclear plant, is also the first SMR to be grid connected in North America. The project has attracted CAD 1 B (USD 0.8 B) public financing from the Canadian federal government (OECD-NEA, 2023a).

- **PWR-20** is a land-based micro-reactor being developed by the U.S. startup Last Energy. PWR-20 combines proven nuclear technology with innovate systems integration and business-model innovation (Last Energy, n.d.). Last Energy has contracted with a Texas-based high-pressure modular equipment assembler for the oil and gas industry. It aims to deploy a total of 34 reactors in Poland, Romania, and the U.K. starting in 2026, with expected revenue of USD 18.9 B from over 3 decades (Patel, 2023).

- NuScale secured the first U.S. SMR license. **VOYGR** is a scaled-up version, expected to be deployed in 4-, 6-, or 12-packs (NuScale Power, n.d.). The first demonstration project in Idaho, the 462 MW Carbon Free Power Project, secured USD 1.4 B from the U.S. Department of

Energy (OECD-NEA, 2023a). In May 2023, Romania's bid to replace a coal-fired power plant in with 6 VOYGR units got USD 275 M support from a multinational consortium of public-private partners from the U.S., Japan, South Korea and the UAE (World Nuclear News, 2023c).

- **IPHWR-220** is one if India's indigenous nuclear designs, with 14 reactors operational across the country. State-owned Nuclear Power Corporation of India Limited (NPCIL) is offering both 220 and 540 MWe IPHWRs for export (World Nuclear Association, 2023c). Though Sri Lanka signed a civil nuclear cooperation agreement with India in 2015 (Chaturvedi & Manoj, 2015), this has not led to a feasibility study.

- **RITM-200N** is the land-based adaptation of RITM-200, which powers Russia's nuclear-powered icebreaker fleet (World Nuclear News, 2020). The Russian government approved a RUB 506 B (USD 6.9 B) program for new nuclear technologies by 2030, including the construction of the land-based RITM-200N in Yakutia (OECD-NEA, 2023a). The marine-based version, RITM-200S, may be deployed by 2027 to power a copper mine in operated by GDK Baimskaya. Refueling intervals for the plants of this series are 6 years for "N", 5 years for "S", and 10 years for "M". Rosatom expects to commission land-based SMRs in other countries from 2029 (Modern Power Systems, 2021).

- **ACPR-50S** is China General Nuclear Power (CGN)'s floating nuclear power design, built to provide electricity, freshwater, process heat, and cooling for shore areas and islands (CGN & CNPRI, 2017). This reactor is the floating version of ACPR50, whose development work started in 2009 (Lobner, 2021).

- Nuclear fuel cycle innovator Holtec International is developing **SMR-160**, leveraging proven design concepts and supply chain partnerships (Holtec Intl, 2019). The company secured USD 116 M from the U.S. Department of Energy to advance reactor design, engineering, and licensing.

- **Rolls-Royce SMR** has attracted over GBP 500 M (USD 688 M) in public and private funding commitments for reactor development and deployment, but needed more funds to materialize to continue its work (Nuclear Engineering International, 2023; Rolls Royce SMR, n.d.)

- Korea Atomic Energy Research Institute (KAERI) is developing **SMART**, and has attracted KRW 480 B (USD 420 M) for the development and design approval from the Korean government and industrial leaders.

- **NUWARD** is the Électricité de France (EDF) Group's foray into SMR technology. With EUR 500M (USD 592M) support from the French government, this power plant is designed to support other energy intensive applications such as heat and electricity cogeneration, hydrogen production, district heating, and water desalination (Nuward, 2023).

Russia has proposed to build a nuclear plant with 100 MW capacity for Sri Lanka, plus managing the entire fuel cycle (Proctor, 2023).

6. Barriers and Opportunities

6.1. Financing

Facing a deep economic crisis, Sri Lanka defaulted on all international sovereign bonds on May 2018, the first time in her history (IMF, 2023). While working through an IMF restructuring package, foreign financing availability and costs are limited. While this is a barrier for nuclear deployment, the same is true for funding LNG infrastructure.

Russia completed 11 reactor builds in six countries 2000-2021, partially by offering attractive state-backed financing (Bowen, 2022). At the beginning of 2022, 13 Russian reactors were being developed abroad. Organization for Economic Co-operation and Development (OECD) countries, such as France, South Korea, and the U.S., are subject to a nuclear arrangement, which limits key loan terms for their reactor exports, including minimum interest rates and repayment terms, disadvantaging them vis-à-vis Russia and China (Bowen, 2022). In July 2023, the OECD increased the maximum repayment term to 22 years (vs. 18) added further repayment flexibilities (OECD, 2023). Furthermore, the U.S., Canada, France, the U.K., Japan, South Korea, and the UAE, are to initiate the International Bank for Nuclear Infrastructure at the UN Framework Convention on Climate Change (COP28) conference later this year (Sondgeroth, 2023).

6.2. Knowledge Base

One barrier to nuclear deployment in Sri Lanka is the low level of nuclear-related human resource. This can be rectified by incorporating nuclear power engineering modules into the programs at various domestic universities.

Basic misunderstandings about nuclear technology allows groups to perpetuate myths that have hindered its growth (Angwin, 2020; Goldstein & Qvist, 2019). Such efforts can be seen regarding Sri Lanka's bid to build nuclear power as well (Balachandran, 2023), as demonstrated by The Association of Professional Sri Lankans in the UK (2023). Chief among these is the conflation of nuclear energy with nuclear weapons (Byrne et al., 1998), though the two have different supply chains, risks, and regulations. Sober educational programs and stakeholder engagement can encourage technology conversations to be evidence-based and risk-informed (Juma, 2016).

6.3. Foreign Influence

As Europe's rude awakening made clear, dependence on Russian energy comes with strings attached (İşeri & Özdemir, 2021). Due to sanctions against Russian banks, Bangladesh is repaying the loan it took for Rooppur in Chinese Yuan to avoid the SWIFT cross-border banking system, and component deliveries are getting delayed (Islam, 2023; World Nuclear News, 2023a).

On the other hand, as a leader of the non-aligned movement, Sri Lanka has a long history of collaborating with Russia (and previously the USSR). The Russia-Sri Lanka intergovernmental agreement on cooperation and mutual assistance, entered in June 2021, noted the prospects in peaceful use of nuclear energy (Gubin, 2022).

6.4. Regulatory Framework

Sri Lanka established the Nuclear Energy Programme Implementing Organization under the Ministry of Power in 2019. Sri Lanka needs to advance the Atomic Energy Act No. 40 of 2014 into a robust regulatory framework that covers issues such as jurisdictional responsibility, radiation protection, and environmental protection (IAEA, 2022).

7. Conclusion

Table 4 lays out the options for Sri Lanka’s electricity growth, and how each option fares along the energy trilemma. Energy is the “ability to do work.” Curbing affordable and reliable energy, such as banning new coal power plants, may retard Sri Lanka from climbing the energy ladder of progress. While sustainable, solar and wind are not reliable energy sources. Investing in LNG will be more expensive than coal, ties up precious hard currency, and has unclear environmental benefits.

	Reliable	Affordable	Sustainable
Coal	✓	✓	✗
Solar + Wind	✗	✓	✓
LNG + Solar + Wind	✓	✗	✗
Nuclear	✓	Long Term: ✓	✓

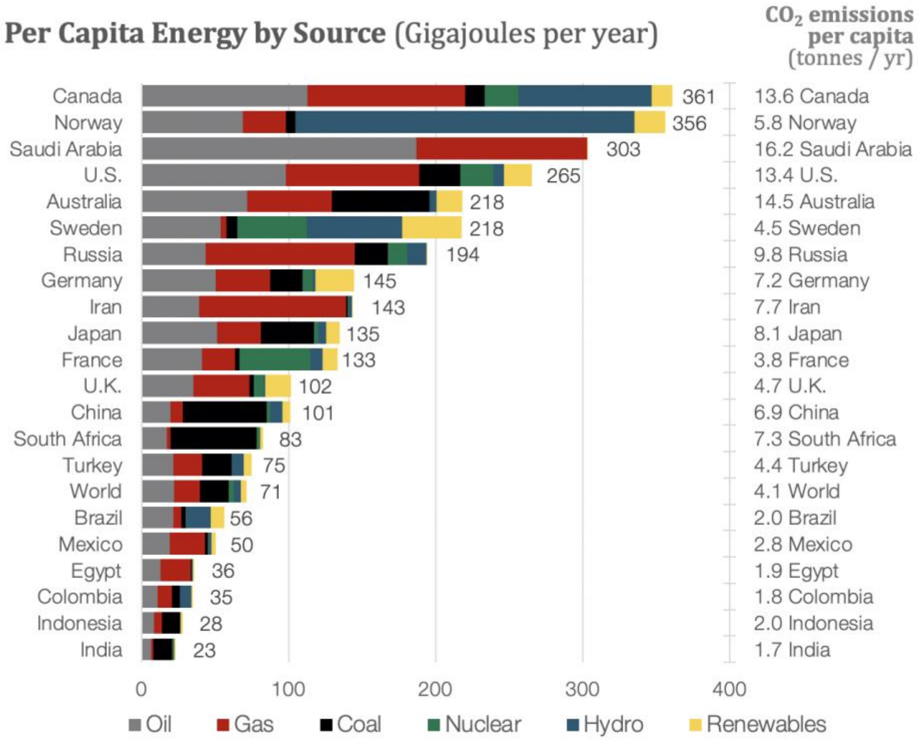
Table 4: Sri Lanka's electricity growth trilemma

Kenyan sustainable development leader Calestous Juma (2016) explored how developing countries can catch up to developed ones by using platform technologies that enable step-changes in efficiency. Nuclear energy is such a technology, able to underwrite a prosperous and sustainable society. With a long timeframe to study, prepare, and deploy, the earliest the LTGEP expects nuclear energy in Sri Lanka is 2037. With concerted effort, Sri Lanka can meet or beat this timeframe to add nuclear energy to the mix. CEB’s mandate is energy security to benefit all of society, not chase short-term profitability. This outlook makes long-lived nuclear energy assets similar to CEB’s major hydro projects, which helped Sri Lanka achieve past socioeconomic goals.

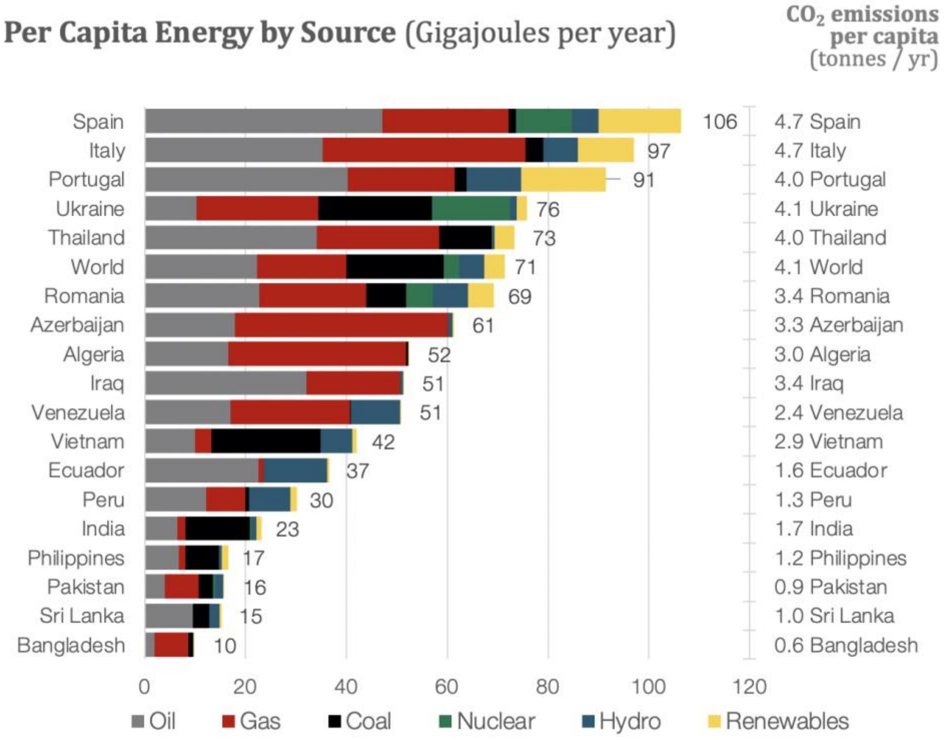
Juma asserts that a primary function of leadership is to chart new paths for society. Sri Lanka’s present economic crisis presents both risks of stagnation and opportunities for inclusive growth. Decisions about energy, an essential economic input, need to be guided by ethical values that reflect the demand for inclusive innovation, better use of technical advice, a greater public understanding of science, and a proactive adjustment of social institutions.

Given the limited ability to fund major energy infrastructure projects, Sri Lanka needs to carefully consider how to build reliable and sustainable nuclear energy and avoid locking in expensive and unsustainable LNG. Sri Lanka should initiate a competitive bidding process, inviting many nuclear vendors and financiers and choose the best option for the country.

8. Appendix A: Energy and Carbon



Sources: BP Statistical Review of World Energy (2021), UNDP (2019), emissions from fossil combustion only, per IPCC Guidelines for National GHG Inventories (2006)



Sources: BP Statistical Review of World Energy (2021), UNDP (2019), emissions from fossil combustion only, per IPCC Guidelines for National GHG Inventories (2006)

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