Electricity Generation Costs by Technology

Moses Jeremiah Barasa Kabeyi *

22064693@dut4life.ac.za; moseskabeyi@yahoo.com

Industrial Engineering Department, Durban University of Technology, Durban South Africa
Oludolapo Akanni Olanrewaju

oludolapoo@dut.ac.za

Industrial Engineering Department, Durban University of Technology, Durban South Africa
*Corresponding Author, contacts: 22064693@dut4life.ac.za; moseskabeyi@yahoo.com

Abstract

The cost of power generation and related technology is an important dimension of energy sustainability since it affects the final price of electricity, choice of technology mix and overall sustainability of the power system. Levelized cost is a simple metric hence widely used to compute the unit cost of power generated from power generation technologies. Limitation of the metric includes lack of consideration for key parameters like inflation, power integration costs, and system costs whose integration would provide a more comprehensive metric for evaluating power generation projects, and the entire power system. The study showed that the Levelized costs of electricity generation for the low carbon technologies have reduced significantly and are now cost competitive with the conventional fossil fuel generation technologies although specific costs are country specific. It was demonstrated that large solar power plants supply cheaper power compared to onshore wind, coal power plants and natural gas power, although it may vary in some factors based on local condition since various factors affect the cost of generation from one place to another. The capital cost of power plants varies widely based on technology as well as within same technology. Fuel cells have the highest capital cost among power plants investigated followed by offshore wind and advanced nuclear power plants. Gas turbines have some of the lowest capital costs. noted that the average price of unit cost of renewable sources namely small PV, largescale PV, onshore and offshore wind as well as biogas has been on a declining trend over the last decade. On the other hand, the average unit price of fossil fuel sources i.e., natural gas, hard coal and lignite coal has been growing. Nuclear, which is a clean non fossil fuel experienced growth in unit price of power which may affect its competitiveness in the energy transition.

Key words: Electricity price; levelized cost of energy; electricity generation; life cycle cost; generation planning; power generation; sustainability; sustainable energy

1. Introduction

Power generation technologies incur a variety of different costs that can be divided into ,three general categories namely wholesale costs which are costs paid by utilities in acquiring and distributing electricity, retail costs which paid by electricity consumers, and external costs, or externalities, which are costs imposed by the society or community(M. J. B. Kabeyi & A. O. Olanrewaju, 2022) . The Levelized cost of electricity (LCOE) is a techno-economic parameter used to describe the unit cost of power generated from a selected power plants by taking into account costs like initial investment, operation and maintenance costs among others for an objective comparison of energy sources(Elisa Veronese et al., 2021). The main drivers for electricity generating costs are the construction, fuel costs, CO_2 emissions costs, and operation and maintenance costs. These factors are influenced by the size of the units used, hence the effect of economies of scale which tend to reduce unit costs for larger units. Even though wind turbines and solar PV ae modular in nature, there is significant cost reduction developed in wind or and solar farms(International Energy Agency, 2020).

The Levelized cost of energy (LCOE), or Levelized cost of electricity, is used to measure the lifetime cost of energy generation or production by a given system. The LCOE facilitates the comparison of costs associated with various forms of energy. The metric is applied to determine the average cost of producing one kilowatt hour (kWh) of electricity over the generating asset lifetime. LCOE computes costs associated with a system like installation, operation, maintenance, and fuel costs all presented as a single figure. It is very straightforward and easy to understand and apply in comparing various energy sources and technologies (Hoymiles, 2020; M. Kabeyi & O. Olanrewaju, 2021).

Wholesale costs of electricity include capital investment cost, operations & maintenance (O&M), transmission and distribution costs, and decommissioning cost. The wholesale costs may be passed as a whole or partially to consumers based on the local regulatory environment. These costs are typically represented in dollars'/megawatt hour (wholesale). These costs are important because they affect consumers directly while governments use them in energy policy decisions(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022).

Generation capacity undertaking requires assessment of the competitive value of various generation technologies in the future that may need to be established partly by means of a complex set of modeling systems. Levelized cost of electricity (LCOE) is an estimate of revenue needed to build and operate a power plant over a specified period. Levelized avoided cost of electricity (LACE) refers to revenue available to the generator over the same period. When applied together, as value-cost ratio (the ratio of LACE-to-LCOE or LACE-to-LCOS), a reasonable comparison of first-order economic competitiveness among many technologies is possible using LCOE, LCOS, or LACE individually(U.S. Energy Information Administration, 2022b). Levelized Cost of Electricity (LCOE) is used in the techno-economic evaluation of power plants. Generally, the LCOE is taken as total costs incurred by the power plant divided by the total energy produced in the lifetime.

2. Cost of Power

The cost of solar farms is now has been generally increasing in terms of construction and operations cost but solar farms and wind turbines remain cheaper than fossil fuel power plants. The recent increase in the cost of renewable sources after many years of decline is mainly due to soaring prices for materials, labor, and shipping costs. Prices for coal and natural gas-fired plants have increased of late following Russia's invasion of Ukraine. This has made new onshore wind and solar projects about 40% less than coal or gas plants built from scratch with the gap widening further with time(Bloomberg, 2022). The costs for renewable plants have been decreasing for the last decade because of increase in production of solar and wind equipment surged I addition to technological improvement. The current declines were affected significantly by the chaos in supply-chain caused by the Covid 19 pandemic(Bloomberg, 2022).

The cost of new onshore wind facilities increased by about 7% in the first half of 2022 on the cost of the same in 2021, the cost of fixed-axis solar plants increased by 14%. The prices are however expected return to cost decline trajectories due to strong demand, easing of supply-chain pressures and production capacity especially in China(Bloomberg, 2022)

The New onshore wind is estimated to cost \$46/MWhr, large-scale solar plants cost \$45/ MWhr, new coal-fired plants cost \$74 per MWh, and natural gas power plants cost \$81 per MWh. The costs of generation can be summarized in table 1.

Table 1: Cost of generation for different technologies(Bloomberg, 2022)

	Technology/energy resource	Cost (USD/MWhr)	Remarks
1	Onshore Wind	46	2
2	Large solar	45	1
3	Coal fired plants	75	3
4	Natural gas	81	4

From table 1, it is noted that power from large solar is the cheapest compared to onshore wind, coal, and natural gas power. In the current trend, natural gas which is a fossil fuel is the most expensive. However, various factors affect the cost of generation from one place to another(Moses Jeremiah Barasa. Kabeyi & Akanni O Olanrewaju, 2020; M. J. B. Kabeyi & A. O. Olanrewaju, 2022; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022).

3. Calculation of Levelized Cost

The costs of power generation for different technologies are compared using Levelized cost of energy (LCOE), expressed in USD2010/MWh. Determination of Levelized cost of energy (LCOE) of needs data on all cash flows involved in its lifetime as well as on the amount of energy that is provided by the respective technology. Cash flows reported in an aggregate form based on monetary accounting principles that combine cash flows into different categories of revenues and expenditures occurring at various points and stages in the project lifetime. Costs considered are associated with the power plant construction and operation in line with the approach in IEA (2010). The costs that are excluded are taxes and subsidies and additional costs related to integration of variable sources, while the assumption applied is that a grid is available for electricity transport(IPCC, 2014; M. J. B. Kabeyi & O. A. Olanrewaju, 2021).

Levelized cost of electricity (LCOE) provides an objective basis of comparison for weighted average costs of different electricity generation technologies making it possible to compare different technologies in a more accurate manner. LCOE is however not equivalent to the amount of feed-in compensation and serves as adequate investment decision tool for individual power plants. The actual or exact value of the electricity is determined by daily and hourly variations and weather-related changes which affect demand and supply conditions, and which cannot be substituted with LCOE.

The levelized cost of electricity (LCOE) is a metric used to compare costs of different conversion technologies in power generation on consistent basis. LCOE is also said to be the net present value of all costs incurred by a power plant technology over the lifetime divided by an a discounted total of the energy output over the asset lifetime(IEA & NEA, 2020). Levelized cost of energy often represents the minimum constant price at which power should be sold to break even over the lifetime of the power plant. The analysis however makes several assumptions on non-financial costs like environmental impacts, local availability, etc., making it controversial(IEA & NEA, 2020). The costs included include initial investment, the operation and maintenance (O&M) costs, the fuel cost and cost of consumables, when applicable. Energy produced can consider the depreciation rate of the plant and equipment (Elisa Veronese et al., 2021). The formulation is here given just as an example of classical LCOE:

$$\mathrm{LCOE} = \frac{\mathrm{CAPEX} + \sum_{t=1}^{n} \frac{\mathrm{OPEX}(t)}{(1+\mathrm{WACC_{nom}})^{t}}}{\sum_{t=1}^{n} \left[\frac{\mathrm{Utilisation_{0}} * (1-\mathrm{Degradation})^{t}}{(1+\mathrm{WACC_{real}})^{t}}\right]} \quad [€/\mathrm{kWh}]$$

(1)

Equation 1 is the formula for Levelized cost where CAPEX is the total investment expenditure for the year t = 0, OPEX(*t*) the cost of operation and maintenance expenditure in year *t*, $\mathrm{WACC_{nom}}$ is the nominal weighted average cost of capital per year, $\mathrm{WACC_{real}}$ the real weighted average cost of capital per year, $\mathrm{Utilization_0}$ represents the initial utilization in the year *t* = 0 (without considering degradation). Degradation refers to the annual degradation of the nominal power of the system, *n* represents the economic lifetime energy system, and *t* stands for the year of lifetime. For solar power plants, other important power generation related costs are insurance costs, the tracking factor which adjusts solar resources to real incident solar energy, and performance factor. The performance factor converts the total available solar resource into the real amount of electricity produced by the system per Watt installed (Elisa Veronese et al., 2021; Elisa Veronese et al., 2021).

4. Power System Security and Related Costs

The reliability of a power system refers to the ability of an electric power system to meet demand for electricity to accepted levels of standards and volumes. Energy security refers to the reliability of electricity regimes while adequacy refers to the balance reliability. Power system security refers to the ability of a power system to withstand sudden perturbations in electricity s supply(Aizenberg & Perzhabinsky, 2019; Frew et al., 2019). Since supply security is a collective responsibility, the payments for security should be set centrally. Adequacy level regulation can also be done centrally for traditional electric power systems or can be decentralized in liberalized power systems. All adequacy management methods defines specific mechanisms of price setting to ensure reliable power supply, levels of new generating powers, expansion of transmission capacity, technology choice for power generation and storage(Frew et al., 2019).

4.1. Reinforcing Transmission and Distribution network costs

4.1.1. Reinforcing Distribution Costs

The distribution network might need to be reinforced and renovated to handle variable renewable. This is because the power grid was originally designed to transport power from central stations for further distribution to end users in a one directional flow through the distribution network. On the other hand, photovoltaic and other distributed sources are predominantly used in commercial and residential buildings and are therefore connected to the distribution grids which are low and medium voltage grids (Baker, 2022; Barnes, 2021).

4.1.2. Reinforcing transmission network costs

The growing use of renewable sources of energy particularly in decentralized generation has introduced new challenges for the transmission grid, just like it has done for the distribution network. Growing self-consumption by prosumers at distribution level modifies the national demand profile while the residual variable renewables fed to the grid can cause over voltage. And reverse power flows at the connection points between the transmission and distribution grids and dynamic challenges like decrease of the system inertia and short-circuit levels. Diffusion of large-scale VRES power plants connected to the transmission grid causing undue stress to grid infrastructure because of handling additional share of variable and intermittent power. Fixing these grid challenges requires reinforcing grid infrastructures and expanding transport capacity of power lines. (NS Energy, 2015).

Investment in control systems to reroute power flows in such a way that power system security is enhanced in the presence of high share of VRES is another option. Apart from infrastructures like lines and substations, a few flexibility tools can be applied, use of control devices, e.g. phase-shifters and flexible AC transmission systems (FACTS), to the electricity markets tools like demand response can be used. These options need significant investment costs to be embedded into reinforcing transmission network costs(M. J. B. Kabeyi & A. O. Olanrewaju, 2022; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022).

It is necessary to compute the reinforcement actions needed for the security of the power system security. The evaluation of these costs requires detailed network studies, especially power flow computations and dynamic stability studies, for most frequent operating conditions. Another approach is development of a power flow model involving estimation of the transmission costs of the investment that is planned by the national transmission system operator (TSO) for RES integration as per the Annual Development Plan(NS Energy, 2015). The resultant expression for transmission reinforcement cost for a solar system can be as follows; follows(Vitzthum, 2013)..

$$C_{\mathrm{trans}} = \frac{\sum_{m}^{\mathrm{macroregions}} \mathrm{Inv}_{\mathrm{TSO,\ RES\ int}}(m)}{\sum_{m}^{\mathrm{macroregions}} \mathrm{Prod}_{\mathrm{VRES,\ 2030}}(m) * \mathrm{PV\_lifetime}} \tag{5}$$

From equation 5, $\mathrm{InvTSO}_{,\mathrm{RES\ int}}$ (m) is total investment by the TSO for RES integration in the macro region m expressed in €, $\mathrm{Prod}_{\mathrm{VRES,2030}}$ (m) is added or extra production of VRES (wind and PV) is future or expected production in macro region m in MWh, and PV-lifetime refers to service lifetime of PV power plants in years.

4.2. Adequacy Costs

Adequacy in a power system refers to the ability of the system to supply consumers with electricity and required as required at any time. Tho realizes this requires enough reserves of electricity capacity, enhancing the transmitting capacity and provision of continuity of fuel supply to the power stations. This form of supply security needs a form of public good and adequacy takes the form of private good in power systems that are liberalized(Aizenberg & Perzhabinsky, 2019; Frew et al., 2019). Adequacy costs are related to system reliability and security of supply resulting from increased penetration of variable renewables. Adequacy costs are evaluated in a similar manner to transmission costs starting from TSO Investments, whose aim is to guarantee quality of the service in the present RES integration objective. Similar, steady-state, and dynamic studies are required for a reasonable cost estimation e.g. previous case(NS Energy, 2015).,

4.3. Curtailment Costs

The curtailment costs are indirect costs used to evaluate the economic losses resulting from curtailed energy for grid stability purposes. This cost component is evaluated as a direct reduction in production of power plant. The reduction is expressed as a percentage generation curtailed for each macro region in respect of the macro regional power generation(Elisa Veronese et al., 2021).

4.4. Balancing Costs

Balancing costs are introduced to capture the impacts variable renewable energy sources (VRES) on thermal power plants which must be increasingly used to cover peak demand. Balancing costs include decay of efficiency and the start-up costs. These costs are estimated by enlarging the energy system model to account for time-dependency of transient operations of fossil fuel generators when the hourly dispatch optimization of the energy system is carried out. The time-dependent constraints added include the start-up costs and ramp constraints which are expressed as functions of plant downtime and technology applied and efficiency decay at partial load when the power plant is not operating normally mainly in the form of additional fuel consumption with respect to nominal condition operating conditions(Frew et al., 2019; Vitzthum, 2013).

4.5. Capital Costs of Power Plants

The real and estimated costs of power plants tend to vary significantly. Real-life costs can diverge significantly from those estimates. Capacity factors can also be used to compare power plants and can be as low as 10-20% for some wind and solar applications, up to 50% range for offshore wind and as high as 90% for the most reliable nuclear and geothermal power plants(Kabeyi, 2019; M J B Kabeyi & A O Olanrewaju, 2020). The average capacity factor of all commercial nuclear power plants in the world in 2020 was 80.3% which is less than the 83.1% for 2019. This value however includes outdated Generation II nuclear power plants Although peaking power plants have low-capacity factors, they compensate by charging the highest possible price when they supply power(Frew et al., 2019).

Alpha Ventus Offshore Wind Farm which has a nameplate capacity of 60 MW is the first German Offshore Wind Park . It cost €250 million against an initial estimate of €190 million). The plant generated 268 Gigawatt-hours of electricity in 2012 to realize a capacity factor of just over 50% while the system availability for the same wind farm in 2012 was an average of 96.5 percent. The system availability was reduced in 2013 due to planned maintenance and service measures. Computing the overnight cost based on nameplate capacity of nameplate gives €4167 per Kilowatt but an account of capacity factor, doubles the figure(IWR, 2013).

Geothermal power has relatively low above-ground impact and can supply baseload power and can be used in combined heat and power. Geothermal fluid may contain naturally occurring radioactive materials such as radon and other minerals which can be released into the air causing pollution. High costs per capacity of geothermal e.g. US$200 million for the 45 MW first phase of Þeistareykir Geothermal Power Station and US$330 million for the 90 MW combined two first phases can be offset by high capacity factors(Battye & Ashman, 2009). In a typical case of natural gas power plants, Block 5 of Irsching Power Station in Southern Germany applies a combined cycle system converting 1750 MW of thermal energy to 847 net electricity with the power plant costing €450 million hence €531 per Kilowatt power plant(Vitzthum, 2013).

For floating wind power plants, the Levelized cost of energy (LCOE) wind power increases with the distance from shore. The Lieberose Photovoltaic Park in Germany whose nameplate capacity at opening of 52.79 MW cost €160 million develop or €3031 per kilowatt. With a yearly output of some 52 Gigawatt-hours the capacity factor is just over 11%. The €160 million figure was again cited when the solar park was sold in 2010. Bhadla Solar Park is the largest solar farm in the world for 2022 located in Rajasthan, India having nameplate capacity of 2,255 MW and cost a total of 98.5 billion Indian rupees to build. which is about 4,3681 rupees per kilowatt(NS Energy, 2015).

Costs vary wildly for different power plants from place to place or time to time and whether interest is included in total cost. Capacity factors and intermittent also impact or influence computation of costs. Power plant lifespan of various power plants also varies with oldest hydropower plants currently with over a century of existence while some nuclear power plants have existed for five or six decades of continuous operation. Wind turbines have exhibited lower lifespan with some being less than 25 years before being retired. Solar panels also exhibit some an aging, which reduces the lifespan(Schwartzman & Schwartzman, 2013). The generation 2 capacity capital costs are expressed often as overnight cost per watt. Estimated costs are.

Table 2: Capital costs of conversion technologies (Feldman et al., 2021; NREL, 2021; U.S. Energy Information Administration, 2022a)

	Power plant technology	Energy source	Cost (USD/kW)

1	Combined cycle power plant	Gas/oil	1,000
2	Combustion turbine	Gas and oil	710
3	Onshore wind	Wind	1600
4	Offshore wind	Wind	6500
5	Solar PV (Fixed)	Solar	830-1800
6	Solar PV (tracking)	Solar	860-2000
7	Battery storage power	VRE	1380
8	Hydropower (conventional)	Hydraulic energy	2752
9	Geothermal	Thermal	2800
10	Coal (with SO_2 and NO_x controls)	Thermal	3500-3800
11	Advanced nuclear	Atomic energy	6000
12	Fuel cells	Hydrogen, methane, etc.	7200

From table 2, it is noted that capital cost of power plant varies widely by technology as well as withing technology. Fuel cells have the highest capital cost followed by offshore wind and advanced nuclear power plants. Gas turbines have some of the lowest capital cost.

4.6. Cost And Performance Characteristic of New Technologies

The various conversion technologies demonstrate variability in cost, with respect to the project size, power plant's location, and access to energy infrastructure like grid interconnections, supply of fuel, and transport. Table 1 shows the weighted average cost for both wind and solar PV, based on regional cost factors for the specific technologies (Anderson et al., 2021; U.S. Energy Information Administration, 2022a). Table 3 shows the cost and performance characteristic of power stations using new modern or future technologies.

Table 3. Cost and performance characteristics of new central station electricity generating technologies.

		First year	Size (MW)	Lead Time	Base O.N. costs $/kW	Opt. factor	Total O.N. Cost ($)/kW
1	Ultra-supercritical coal (USC)	2025	650	4	4074	1.0	4074
2	USC with 30% carbon capture and sequestration (CCS)	2025	650	4	5045	1.01	5096
3	USC with 90% CCS	2025	650	4	6495	1.02	6625
4	Combined-cycle—single-shaft	2024	418	3	1201	1	1201
5	Combined-cycle—multi-shaft	2024	1083	3	1062	1	1062
6	Combined cycle with 90% CCS	2024	377	3	2736	1.04	2845
7	Internal combustion engine	2023	21	2	2018	1.0	2018
8	Combustion turbine— aeroderivative	2023	105	2	1294	1.0	1294
9	Combustion turbine—industrial frame	2023	237	2	785	1.0	785
10	Fuel cells	2024	10	3	6639	1.09	7224

11	Nuclear—light water reactor	2027	2156	6	6695	1.05	7030
12	Nuclear—small modular reactor	2028	600	6	6861	1.10	7547
13	Distributed generation—base	2024	2	3	1731	1.00	1731
14	Distributed generation—peak	2023	1	2	2079	1.00	2079
15	Battery storage	2023	50	1	1316	1.00	1316
16	Biomass	2025	50	4	4524	1.00	4524
17	Geothermal	2025	50	4	3076	1.00	3076
18	Conventional hydropower	2025	100	4	3083	1.00	3083
19	Wind	2024	200	3	1718	1.00	1718
20	Wind offshore	2025	400	4	4833	1.25	6041
21	Solar thermal	2024	115	3	7895	1.00	7895
22	Solar photovoltaic (PV) with tracking	2023	150	2	1327	1.00	1327
23	Solar PV with storage	2023	150	2	1748	1.00	1748

Table 3 shows the various power technologies and the costs. The costs are for a typical facility for the generating technology before adjustment is made for regional cost factors. Overnight costs do not include the interest accrued during power plant construction and development. Technologies having little commercial experience are allowed a technological optimism factor to capture the tendency to underestimate the full engineering and development costs incurred by new technologies in the process of research and development(U.S. Energy Information Administration, 2022b).

4.7. Overnight Costs

Overnight costs do not capture interest during plant construction and development. For technologies having limited commercial experience, a technological optimism factor is used to account for the tendency to underestimate total costs for full engineering and development for new technologies during research and development(U.S. Energy Information Administration, 2022a). There is significant variation in the overnight investment costs even for mature technologies like coal- and gas-fired technologies based on the technology type, size and the country (International Energy Agency, 2020)

4.8. Operations and Maintenance (O&M) Costs

Operation and maintenance costs include marginal costs of fuel, maintenance, operation, waste storage, and decommissioning for the power plant. Fuel costs are highest for oil fired plants followed by coal, gas, biomass, and uranium. Because of high energy density of uranium (or MOX fuel in plants that use this alternative to uranium) and the comparatively low price on the world uranium market measured in units of currency per unit of energy content, fuel costs only are just a fraction of the operating costs of nuclear power plants. The cost balance between capital and running costs favors lower operating expenses for renewables and nuclear and in the other direction for fossil fuels(Frew et al., 2019).

For thermal power plants, particularly oil fired, gas and coal to some extent, the cost of generation is significantly affected by fluctuations in fuel prices. Renewable energy sources are not affected by the fluctuations in the world markets since they do not have furl costs. Most coal power plants get local supply of coal especially for lignite which is of low grade with high moisture content making long distance transportation quiet expensive. Existence of a carbon tax or other forms of CO_2-pricing, can significantly affect the economic viability of fossil fueled power plants. Uranium is rarely affected by fuel cost fluctuations due to the ease and hence practice of stockpiling uranium and less frequent refueling with most Pressurized Water Reactors changing fuel for a quarter to a third of their fuel loading for every one and a half to two years. It is a common practice for uranium fuel suppliers to bear the cost of short-term fluctuations in world uranium prices instead of power plant operators except for long-term price trends which affect the final price of nuclear power generation(Cano-Londoño et al., 2022).

4.9. Market Matching Costs

One limitation of “Levelized cost of electricity" metric is that it disregards the time effects related to matching demand and power generation which occurs at two levels i.e., dispatchability which refers to ability come or go offline also called ramp up and ramp down and degree to which availability profile matches or conflicts with the demand profile.

Ramp rates may be quicker for more modern nuclear power plants than old ones and economics of nuclear power plants may differ significantly.[44][45] Generally the capital intensive power plants like solar, wind,, geothermal and nuclear are disadvantaged economically unless they operate at maximum availability. This is because the LCOE is nearly all sunk-cost capital investment. Power systems with high share of intermittent sources may incur extra costs related to storage or backup generation [46] On the other hand, intermittent sources are more competitive if they are available to generate when demand and prices are high e.g. solar during summer in regions where air conditioning is a major consumer. The influence of energy efficiency and conservation (EEC) is another important factor in costing electricity which is neglected by the LCOE (Bronski, 2014). Energy Efficiency Conservation can flatten or cause a decline of electricity demand. For end use energy systems, it may be more economical invest in energy efficiency and conservation or both simultaneously which leads to a smaller and less costly system(Bronski, 2014; D'Agostino et al., 2022). It is important to consider the whole system's life cycle cost not just the LCOE of the energy source. Other financial considerations like cash flow, income, mortgage, rent, leases, and electricity bills besides LCOE are relevant to end-users(Bronski, 2014).

4.10. External Costs of Energy Sources

External costs are costs that are borne indirectly by the society as a whole as a consequence of using that energy source(D'Agostino et al., 2022). The costs include enabling costs, energy storage, environmental impacts, cost of recycling, and beyond-insurance accident effects. They include cost of relocating residents, evacuation of homes, property damage, etc.(Trinomics, 2022). The performance of solar panels is usually guaranteed for 25-30 years. Recycling a solar panel will cost $20–30 per panel in 2035, which effectively increases LCOE fourfold for PV solar power if panels are replaced after 15 years rather than the expected 30 years(D'Agostino et al., 2022). Studies showed that the cost of generating power from coal or oil would double and cost of electricity production from gas would increase by 30% if external costs like environmental damage and to human health, from emissions like particulate matter, nitrogen oxides, chromium VI, river water alkalinity, mercury poisoning and arsenic emissions generated are considered. It was also estimated in the study that external, downstream, fossil fuel costs range between 1%–2% of the EU's entire Gross Domestic Product (GDP), before external cost of global warming are captured(Trinomics, 2022). In the EU, coal has the highest external cost with global warming being the largest part of external cost. It is necessary to develop sustainable energy to reduce external costs of electricity to the society(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022b).

External costs of fossil fuel can be addressed by carbon pricing which is the most favored approach to reduce global-warming emissions through which those who emit carbon dioxide for are charged. Carbon price which is the charge is the paid for the right to emit one tons of carbon dioxide to the environment and takes the form of a carbon tax or a requirement to purchase permits to emit also called allowances to emit(KPMG, 2022).

Based on assumptions on possible accidents, external costs for nuclear power vary significantly but generally are 0.2 and 200 ct/kWh. Nuclear power also works under an insurance framework which limits or structures accident liabilities in line with the Paris convention on nuclear third-party liability, the Vienna convention on civil liability for nuclear damage , Brussels supplementary convention. As for the United States Price-Anderson Act applies(International Atomic Energy Agency, 1996). These potential shortfall in liability is an external cost not included in the cost of nuclear electricity although it is relatively small since it is about 0.1% of the Levelized cost of electricity(Congressional Budget Office, 2008). The beyond-insurance costs for worst-case scenarios are common for nuclear power generation, hydroelectric power plants for large dam failure etc. Since private insurers base dam insurance premiums on limited scenarios, large disaster insurance in hydropower sector is generally provided by the state. Since it is difficult to directly measure external costs since externalities are diffuse in their effect(Walsh, 2017).

5. Global Levelized Cost of Generation

Various approaches and institutions have tried to determine the global Levelized cost of generation. This includes the Bloomberg New Energy Finance which established that it is now cheaper to build new solar or wind farms than new fossil fuels powered power plants to replace retiring power plants. The study further showed that lithium-ion battery storage has competitive Levelized cost of energy with other peak–demand power plants. The study by Blumberg further showed that gas peakers have substantial costs in terms of fuel and external costs of its combustion which include emission of greenhouse and other environmental pollutants(BloombergNEF, 2021).

Wind and solar power has become the least-expensive option for bulk power generation for two-thirds of the world population, 71% of global GDP, and 85% of worlds power production. (BloombergNEF, 2021). It is now cheaper to build a new solar or wind farm to meet electricity demand as replacement for power, than building a fossil fuel fired power plant. In terms of cost, solar and wind is the best choice where firm power generation resources do exist and with growing demand(Osborn et al., 2015).

. It is further argued that Levelized cost of energy storage by the lithium –ion battery is cost competitive with several peak power plants e.g., the of gas peakers and gas turbines are substantial, since they incorporate fuel cost and external costs of its combustion. Like greenhouse gas emission in form of carbon monoxide and carbon dioxide, nitrogen oxides (NO_x), Sulphur dioxide (SO_2)which can damage the human respiratory system and also form acid rain(BloombergNEF, 2021). Nitrogen Dioxide (NO_2) is one of a group of highly reactive gases called oxides of nitrogen or nitrogen oxides (NO_x). Others are nitrous acid and nitric acid. Generally, NO_2 is used as the indicator for the wider group of nitrogen oxides. Which gets in the atmosphere from fossil fuel combustion(United States Environmental protection Agency, 2022). Table 4 shows

Table 4: Global Levelized cost of generation by source in USD/MWhr

	Technology	IPCC (2014) (AT 5% DISCIUNT RATE)	IRENA (2020)	LAZARD (2020)	NEA (2020) AT 7% DISCOUNT RATE	BANF 2021	AVERAGE USD/MWh	Rank
1	PV (utility scale with fixed axis)	110	68	30	56	39	61	4
2	PV (Utility scale with tracking			40		47	44	1
3	PV (residential)	150	164	189	126	-	157	11
4	Solar thermal	150	182	141	121	-	149	10
5	Wind (onshore)	59	53	40	50	41	49	3
6	Wind (onshore)	120	115	86	88	79	98	9
7	Nuclear (LTO)	65	-	164(29) =96.5	69(32) =55	-	72	5
8	Hydro	-	22	47	-	68	46	2
9	Geothermal	60	73	80	99	-	78	6
10	Coal (CC)	61		112	88/110=99	-	91	8
11	Gas (CC)-peak	71	-	117	71	-	86	7

Table 4 shows PV utility scale solar with fixed axis produces the cheapest power while power PV residential is the most expensive on levelized cost basis. Hydro followed by onshore wind are the other cheapest sources of electricity. It shows that size of installation significantly affects the electricity even from the same energy source.

Generally, the cost of renewable energy technologies particularly the photovoltaics and wind has been rapidly falling over the last decade(Jain et al., 2021). This is demonstrated in table54 below.

Table 5 : Electricity production costs for different power plants between 2009 and 2021 (€/MWh)(Jain et al., 2021)

	Energy technology	2009	2011	2012	2013	2015	2018	2021	Average	Rank

1	Nuclear	50	60-100=80	70-105=87.5	-	36-84=60	-	-	69	3
2	Lignite	46-65=55.5	45-100=72.5	-	38-53=45.5	29-84=56.5	45.9-79.8=62.9	103.8-153.4=128.6	63	1
3	Hard coal	49-68=58.5	45-100=72.5	-	63-80=71.5	40-116=78	62.7-98.6=80.7	110.3-200.4=155.35	86	6
4	Natural gas (CCGT)	57-67=62	40-75=57.5	93	75-98=86.5	53-168=110.5	77.8-99.6=88.7	77.9-130.6=104.3	86	6
5	Hydro					22-108			65	2
6	Wind onshore	93	50-130=90	65-118=91.5	45-107=76	29-114=71.5	39.9-82.3=61.1	39.4-82.9=61.15	78	4
7	Wind offshore	-	120-180=150	112-150=131	119-194=156	67-169=118	79.9-137.9=108.9	72.3-121.3=96.8	101	8
8	Biogas	-	-	126	135-215=175	-	101.4-147.4=124,4	72.2-172.6=122,4	137	10
9	Small scale PV	-	-	137-203=170	98-142=120	-	72.3-115.4=93.85	58.1-80.4=69.25	113	9
10	Largescale PV	32	-	107-184=145,5	79-116=97.5	35-180=107.5	37.1-84.6=60.85	31.2-57=44,1	81	5

From table 5, it is noted that the average price of unit cost of renewable sources namely small PV, largescale PV, onshore and offshore wind as well as biogas has been on a declining trend. On the other hand, the average unit price of fossil fuel sources i.e., natural gas, hard coal and lignite increased between 2009 and 20221. Nuclear, which is a clean non-fossil fuel experienced growth in unit price over the same period.

In the UK, the feed-in tariff of £92.50/MWh at 2012 prices is an equivalent of €131/MWh) today based taking care of inflation compensation set in 2013 for the new nuclear power plant to be built at Hinkley Point C, with life of 35 years. This figure was less than the feed-in tariff for large photovoltaic and offshore wind power plants but more than onshore wind plants(Department of Energy and Climate Change, 2013; UK Government, 2018).

For the case of Germany, there is evidence from the bidding processes of significant cost reductions for renewables since the year 2017 with one bidder for offshore wind farms, dispensing entirely with public subsidies and was ready to finance the project through the market alone. The highest price of subsidy price awarded was 6.00 ct/kWh(Müller, 2013). . In bids for onshore wind farm projects, an average payment of 5.71 ct/kWh was realized, and 4.29 ct/kWh was achieved in the second round of bidding. In the year 2019, bids for new offshore wind farms in the United Kingdom, were as low as 3.96 pence per kWh (4.47 ct). This also marked the end of subsidies on new offshore power projects. Meaning households will not spend extra costs supporting new wind projects(Ambrose, 2019; Kabeyi, 2022).

In Portugal bids for photovoltaic plants, had the cheapest project priced at 1.476 ct/kWh against a bidding tariff set at 45 euros MWh (Euractiv, 2019). This was notably the lowest price in the world, which provides evidence that energy transition can strongly accelerate investment and the penetration of renewables and even achieve low prices. In Britain, gas is the largest source of electricity at 40% as of 2022 with varying cost of power. As a measure to reduce the share of high carbon sources, it the government annually auctions contracts for difference power plants with low carbon emissions specially offshore wind(M. Kabeyi & O. Olanrewaju, 2022; Lempriere, 2022). Before year 2022 generators always received subsidies for electricity supply but the reverse is currently happening as they are paying the state instead because renewables are now self-sustaining(Kabeyi, 2012; The Week, 2019).

For France which heavily relies on nuclear power, the Fukushima Daiichi nuclear disaster has forced introduction of new safety investments to upgrade the French nuclear plants by about €4/MWh. For large scale solar power of capacity 50–100 GWh/year, the estimate of €293/MWh is provided while small household plants generating 3 MWh/year, cost between 400 and €700/MWh, based on the location. In France, solar remains the most expensive renewable source of electricity but the technology has become competitive due to higher efficiency and longer lifespan of photovoltaic panels and reduced cost of production since 2011to reach the cost of less than €50/MWh.

6. Results and Discussion

Energy experts, policymakers, and modelers need at their disposal reliable information on the cost of power generation as the global community puts in place measures to ensure that power generation is reliable, affordable, and increasingly greener. Important data is the cost of power generation from coal, nuclear, natural gas, and renewable technologies. An important addition information on the storage costs, the long-term operation of nuclear power plants, hydrogen and fuel cells which are important elements of renewable energy power generation(IEA & NEA, 2020). Power systems with low carbon value have complex interactions of different technologies having different functions to ensure reliable supply. System effects and system costs are identified using broader value-adjusted LCOE, or VALCOE metric (IEA & NEA, 2020; Kabeyi & Olanrewaju, 2023).

Studies show that projected costs of generating electricity Levelized costs of electricity generation for the low-carbon conversion technologies have been reducing and headed below the costs of conventional fossil fuel generation. For many countries, the renewable energy costs have decreased, and their costs are now competitive, in LCOE terms, with dispatchable fossil fuel-based technologies. Electricity cost from new nuclear power plants remains stable, but the long-term operation of nuclear power plants constitutes a least cost power option for low-carbon power. Gas fired power generation coat has reduced because of low gas prices and giving them an attractive role in the energy transition(IEA & NEA, 2020; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022a).

With moderate emission costs of about USD 30/tCO_2 studies show that renewables are competitive based on Levelized cost of power. Largescale deployment of solar PV, under favorable climatic conditions is cost competitive. For wind power generation, the cost of offshore wind has significantly reduced over time. The median LCOE for offshore wind has reduced from still more than USD 150/MWh, to less than USD 100/MWh over five years' period. For Hydropower, running river and reservoir technologies can provide competitive alternatives at suitable sites although cost vary widely with specific sites. The Levelized cost of nuclear power also reduced between 2015 and 2020. Overnight construction costs were reduced due to learning from first-of-a-kind (FOAK) projects. The Levelized cost of energy (LCOE) for nuclear power plants are provided for nth-of-a- kind (NOAK) plants to be completed by 2025 or thereafter which show significant reduction in Levelized cost and the development period (IEA & NEA, 2020). Nuclear electricity has the lowest expected costs in 2020 compared to 2015 with a lot. regional disparity. Average overnight construction costs have been reduced due to learning from first-of-a-kind (FOAK) projects in many countries. Nuclear power remains the dispatchable low-carbon technology with the lowest expected costs in 2025 with similar contribution at comparable costs coming from hydropower which however but remain highly dependent on the natural endowments of different countries. Nuclear power plants are increasing, becoming more competitive and affordable than fossil fuel-based generation, like coal-fired power generation. Studies show that power from nuclear long-term operation (LTO) by lifetime extension is very competitive in terms of least cost option for low-carbon generation compared to new power nuclear plants and likewise for all other power plants (International Energy Agency, 2020).

Nuclear is low carbon dispatchable technology with the lowest projected costs same for hydro reservoirs but they depend natural endowments of countries. Nuclear plants are more affordable compared to coal-fired plants. Although gas-based combined-cycle gas turbines (CCGTs) are competitive in some countries, their Levelized cost of energy is dependent on the natural gas prices and carbon emissions in individual regions. Power from nuclear long-term operation (LTO) by lifetime extension is quite competitive and remains not only the least cost option for low-carbon generation compared to building new power (IEA & NEA, 2020). Therefore, extension of operating live of nuclear power plants is an attractive measure for most nations.

The study showed that the Coal- and gas-fired units with carbon capture, utilization, and storage (CCUS), based on data from the United States and Australia having a carbon price of USD 30 per ton of CO_2, are not competitive with unmitigated fossil fuel-plants, nuclear energy, and in many variable renewable generation plants in many countries. It was observed that the CCUS-equipped plants will be complement in the power mix only if the carbon costs are higher (International Energy Agency, 2020). The major limitations of the LCOE are that the values are based on a Levelized average lifetime cost approach, which uses discounted cash flow (DCF) method. The Costs are calculated at the plant level (busbar), without capturing transmission and distribution costs, which may be significant for most installations. The LCOE also doesn't capture other systemic costs or externalities beyond plant-level CO_2 emissions like methane leakage in extraction and transport of natural gas. It may be argued that the system effects of different technologies, like cost of variability of wind and solar PV at higher penetration rates ought to be considered (IEA & NEA, 2020; Kabeyi, 2022).

The use of Levelized cost comparisons tends to overvalue intermittent technologies compared to dispatchable conversion technologies. Additionally, they tend to overvalue wind compared to solar conversion technologies. To facilitate more meaningful comparison, it is important to integrate the differences in generation profiles, related market variations, and life-cycle costs for the production technologies. There are implications of this market-based framework for the appropriate procurement auctions design created for implementation of renewable energy procurement mandates, efficient structure of production tax credits and the evaluation of the additional costs incurred for integrating intermittent generation to the power grid(Joskow, 2011).

The system LCOE' is a metric used for evaluation of variable renewable energy (VRE) within a short and long-term perspective. The metric considers the implication of variable renewable e.g. reduction of full load hours for the conventional power plants. The System LCOE considers the increase in system costs because of variable renewable sources. Analysis of the Levelized cost of energy for wind and solar for Germany demonstrated that as the variable renewables increase, costs significantly rise. By use of the system LCOE, there is improved estimation and comparison of the social value of different types of variable renewable sources(Joskow, 2011). The cost of renewable energy has continued to decline, with technologies like onshore wind and utility-scale solar), becoming cost-competitive with fossil fuel sources particularly on a new-build basis maintaining competitiveness with the marginal cost of some existing conventional conversion technologies.

. Based on Lazard's Levelized Cost of Storage Analysis (LCOS 6.0) it is also observed that the cost of storage has reduced across many technologies especially for shorter-duration applications. This is partly driven by evolving preferences about battery chemistry. Focus shifts t managing intermittency and variability for wind and solar as the costs of utility scale solar and wind generation decline and compete with marginal cost of conventional technologies. Green and blue hydrogen has growing potential disruptive and strategic role in managing renewable energy intermittency and variability. Many other factors have a potential effect on the Levelized cost of energy (LCOE) e.g. value vs. energy value, cost of system or network upgrades, transmission and distribution costs, integration related costs like congestion, important and significant licensing costs, compliance costs for environmental regulations like carbon emissions offsets or emissions control systems. Others are potential social and environmental externalities like social costs and rate consequences for investors and consumers who cannot afford distributed generation options, and long-term residual and societal consequences of conventional technologies like nuclear waste disposal and impact of pollution (Kabeyi, 2012; Lazard, 2020).

Some renewable energy conversion technologies are cost-competitive with conventional for specific circumstances. The levelized cost of renewable energy is significantly affected by the Investment Tax Credit ("ITC") and Production Tax Credit ("PTC") and therefore they remain important for analysis. For conventional technologies, the fuel price changes can materially affect the Levelized cost of energy (LCOE). However, when competing with renewable energy generation technologies it may be important to consider major issues like dispatch characteristics like baseload and/or dispatchable intermediate capacity compared to those of peaking or intermittent generation technologies. For utility scale technologies important considerations also include the cost, and availability finance which is particularly important for renewable energy generation technologies (Lazard, 2019, 2020, 2021).

Analysis of the unsubsidized LCOE indicates significant historical cost reductions for utility-scale renewable energy power generation technologies like wind and utility-scale solar with main drivers being reducing capital costs, technological advances, and growing competition among players leading to higher efficiencies. Although PV has undergone dramatic LCOE reduction, the industry seems to have matured, leading to a decline in reduction rates. The main challenge with Solar PV and wind is lack the dispatch characteristics, that are associated with conventional technologies hence the need for storage. There are many cases where capital costs of renewable energy technologies have converged with some conventional technologies for power generation which when coupled with increase in operational efficiency for renewable energy technologies, has created convergence in Levelized cost of energy between conventional and renewable energy technologies. Although we now have convergence in LCOE of certain renewable energy technologies and conventional generation technologies, comparisons should further consider factors like location i.e. centralized vs. distribute) and dispatch characteristics(Lazard, 2020, 2021) for better choice and decision making.

Because the Levelized cost of energy (LCOE) does not account for factors like system costs and other non-project costs, there is need to identify and consider, model, and predict other costs the power system to help policy-makers and network planners in in selecting and developing new energy projects particularly with respect to sustainable energy e.g. variable and intermittent renewables, and the subsequent costs to the power system operator (Sklar-Chik et al., 2016).

7. Conclusions

All power generation technologies have some degree of variability in terms of cost, since size of the project, project location, location, vicinity, and access to access to key infrastructure like the grid interconnections, means of transport and fuel supply. The standard LCOE metric is widely accepted and used in power generation projects worldwide. Some variations of the LCOE metric can capture inflation and the Levelized profit of energy. Levelized cost of energy (LCOE) is an important metric used for technology selection and decision for electricity projects. There is a need to account for limitations of Levelized cost of energy metric for accurate analysis and due diligence, when making decisions having widespread social, economic, and environmental impacts in the long run. LCOE metric remains an important tool for decision making because it is relatively simple and easily accessible metric for project evaluation. However, LCOE as a metric should be used in conjunction with other project metrics and methodologies to adequately consider important parameters for sustainable energy development.

The main limitation of variable renewables is that their adjusted LCOE (VALCOE) metric shows that their system value tends to decrease as their share in the power supply increases. It was however demonstrated that large solar power plants are the cheapest compared to onshore wind, coal, and natural gas power. However, various factors affect the cost of generation from one place to another, and capital cost of power plants varies widely by technology as well as within the same technology family due to many other factors. Fuel cells have the highest capital cost followed by offshore wind and advanced nuclear power plants among power plants investigated. Gas turbine power plants have some of the lowest capital cost requirements compared with renewables. The study also showed that the average unit cost of renewable sources of energy namely small PV, largescale PV, onshore and offshore wind as well as biogas has been reducing over the last decade. On the other hand, the average unit price of fossil fuel sources i.e., natural gas, hard coal and lignite has been increasing. Nuclear, which is a clean non fossil fuel experienced growth in unit price of power over the same period.

This study showed that the cost of electricity generation for carbon power plants and technologies have been reducing and are increasingly becoming cheaper than the costs of conventional fossil fuel technologies. Onshore wind is expected to have, lowest average Levelized costs of electricity generation by 2025. For areas with favorable climatic conditions, solar PV, be very cost competitive if deployed at large scales and under. Offshore wind has also decreased significantly making it competitive. With suitable sites, the running of river and reservoir hydropower can provide very competitive alternatives, but their costs remain very site-specific.

References

Aizenberg, N., & Perzhabinsky, S. (2019). Generation adequacy of electric power systems in market price setting. *E3S Web Conf.*, *114*, 03006. https://doi.org/https://doi.org/10.1051/e3sconf/201911403006

Ambrose, J. (2019, 20 September 2019). New windfarms will not cost billpayers after subsidies hit record low. *The Guadian*. https://www.theguardian.com/environment/2019/sep/20/new-windfarms-taxpayers-subsidies-record-low#:~:text=New%20windfarms%20will%20not%20cost%20billpayers%20after%20subsidies%20hit%20record%20low,-This%20article%20is&text=The%20UK's%20next%20wave%20of,price%20for%20the%20first%20time.

Anderson, J., Rode, D., Zhai, H., & Fischbeck, P. (2021). Reducing carbon dioxide emissions beyond 2030: Time to shift U.S. power-sector focus. *Energy Policy*, *148*, 111778. https://doi.org/https://doi.org/10.1016/j.enpol.2020.111778

Baker, D. (2022, Jene 2022). Renewable Power Costs Rise, Just Not as Much as Fossil Fuels. *Bloomberg*. loomberg.com/news/articles/2022-06-30/renewable-power-costs-rise-just

Barnes, R. (2021). The True Cost of Energy: Fossil Fuels vs Renewables. *Engineering with Rosie*. https://rosemary-barnes.medium.com/the-true-cost-of-energy-fossil-fuels-vs-renewables-fc5e0ce3a16c

Battye, D. L., & Ashman, P. J. (2009). *Radiation associated with Hot Rock geothermal power* Australian Geothermal Energy Conference 2009, https://www.geothermal-energy.org/pdf/IGAstandard/AGEC/2009/Battye__Ashman_2009.pdf

Bloomberg. (2022, 1 July 2022). *Renewable power costs rise, just not as much as fossil fuels*. Bloomberg. Retrieved 28 November 2022 from https://www.engineeringnews.co.za/article/renewable-power-costs-rise-just-not-as-much-as-fossil-fuels-2022-07-01/rep_id:4136

BloombergNEF. (2021). *BNEF Executive Factbook*. B. (BNEF). https://assets.bbhub.io/professional/sites/24/BNEF-2021-Executive-Factbook.pdf

Bronski, P. (2014, May 29, 2014). You Down With LCOE? Maybe You, But Not Me. https://rmi.org/blog_2014_05_29_you_down_with_lcoe/

Cano-Londoño, N., Heriberto, C., & Krisztián, B. (2022). Integrated Sustainability Assessment: Exergy, Emergy, Life Cycle Assessment [Methods]. *Frontiers in Sustainability*, *3*. https://doi.org/https://doi.org/10.3389/frsus.2022.921874

Congressional Budget Office. (2008). *Nuclear Power's Role in Generating Electricity*. https://www.cbo.gov/sites/default/files/110th-congress-2007-2008/reports/05-02-nuclear.pdf

D'Agostino, D., Parker, D., Melià, P., & Dotelli, G. (2022). Optimizing photovoltaic electric generation and roof insulation in existing residential buildings. *Energy and Buildings*, *255*, 111652. https://doi.org/https://doi.org/10.1016/j.enbuild.2021.111652

Department of Energy and Climate Change. (2013). *Electricity Market Reform Delivery Plan*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/268221/181213_2013_EMR_Delivery_Plan_FINAL.pdf

Euractiv. (2019). *Portugal's solar energy auction breaks world record*. Euractiv Foundation Retrieved 26 January 2023 from https://www.euractiv.com/section/energy/news/portugals-solar-energy-auction-breaks-world-record/

Feldman, D., Ramasamy, V., Fu, R., Ramdas, A., Desai, J., & Margolis, R. (2021). *U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020*. https://www.nrel.gov/docs/fy21osti/77324.pdf

Frew, B., Stephen, G., Sigler, D., Lau, J., Jones, W. B., & Bloom, A. (2019). Evaluating resource adequacy impacts on energy market prices across wind and solar penetration levels. *The Electricity Journal*, *32*(8), 106629. https://doi.org/https://doi.org/10.1016/j.tej.2019.106629

Hoymiles. (2020). *What is levelized cost of energy and how does it work?* Hoymiles. Retrieved 3 December 2022 from https://www.hoymiles.com/resources/blog/what-is-levelized-cost-of-energy-and-how-does-it-work/

IEA, & NEA. (2020). *Projected Costs of Generating Electricity*. https://www.oecd-nea.org/upload/docs/application/pdf/2020-12/egc-2020_2020-12-09_18-26-46_781.pdf

International Atomic Energy Agency. (1996). *Vienna convention on civil liability for nuclear damage*. https://www.iaea.org/sites/default/files/infcirc500.pdf

International Energy Agency. (2020). *Projected costs of generating electricity*. I. E. Agency. https://iea.blob.core.windows.net/assets/ae17da3d-e8a5-4163-a3ec-2e6fb0b5677d/Projected-Costs-of-Generating-Electricity-2020.pdf

IPCC. (2014). *Technology-specific Cost and Performance Parameters: Annex III*. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf

IWR. (2013, 04/26/2013). *Offshore wind farm alpha ventus produced in 2012 well above target*. IWR. Retrieved 23 November 2022 from https://www.iwr.de/news/offshore-windpark-alpha-ventus-produziert-2012-deutlich-ueber-dem-soll-news23536

Jain, S., Kumar Jain, N., Choudhary, P., & Vaughn, W. (2021). Designing terawatt scale renewable electricity system: A dynamic analysis for India. *Energy Strategy Reviews*, *38*, 100753. https://doi.org/https://doi.org/10.1016/j.esr.2021.100753

Joskow, P. L. (2011). Comparing the Costs of Intermittent and Dispatchable Electricity Generating Technologies. *American Economic Review*, *101*(3), 238-241. https://doi.org/10.1257/aer.101.3.238

Kabeyi, M., & Olanrewaju, O. (2021, March 7-11, 2021). *Development of a cereal grain drying system using internal combustion engine waste heat* 11th Annual International Conference on Industrial Engineering and Operations Management Singapore. http://www.ieomsociety.org/singapore2021/papers/188.pdf

Kabeyi, M., & Olanrewaju, O. (2022, 17-20 Oct. 2022). *Feasibility of Conversion from Diesel Engine to Natural Gas Power Plants* IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, Brussels, Belgium. https://ieeexplore.ieee.org/document/9968428

Kabeyi, M. J. B. (2012). *Challenges of implementing thermal powerplant projects in Kenya,the case of Kipevu III 120MW power station,Mombasa Kenya* (Publication Number 5866) University of Nairobi]. Nairobi. http://erepository.uonbi.ac.ke:8080/xmlui/handle/123456789/11023

Kabeyi, M. J. B. (2019). Geothermal electricity generation, challenges, opportunities and recommendations. *International Journal of Advances in Scientific Research and Engineering (ijasre)*, *5*(8), 53-95. https://doi.org/10.31695/IJASRE.2019.33408

Kabeyi, M. J. B. (2022). Potential and challenges of bagasse cogeneration in the Kenyan sugar industry. *International Journal of Creative Research Thoughts*, *10*(4), 379-526, Article IJCRT_218740. https://doi.org/http://doi.one/10.1729/Journal.30042

Kabeyi, M. J. B., & Olanrewaju, A. O. (2020). Feasibility of Wellhead Technology Power Plants for Electricity Generation. *International Journal of Computer Engineering in Research Trends*, *7*(2), 1-16. https://doi.org/https://doi.org/10.22362/ijcert/2020/v7/i02/v7i0201

Kabeyi, M. J. B., & Olanrewaju, A. O. (2020, 14-17 Dec. 2020). Managing Sustainability in Electricity Generation. 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM),

Kabeyi, M. J. B., & Olanrewaju, A. O. (2022, 25-27 Jan. 2022). The Use of Smart Grids in the Energy Transition. 2022 30th Southern African Universities Power Engineering Conference (SAUPEC),

Kabeyi, M. J. B., & Olanrewaju, O. A. (2021, 7-8 Oct. 2021). Conversion of a Flash Power Plant to Organic Rankine System for Olkaria Geothermal Power Plants. 2021 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME),

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022a). Performance evaluation of Kipevu-III 120 MW power station and conversion to dual-fuel power plant. *Energy Reports*, *8*(16), 800-814. https://doi.org/https://doi.org/10.1016/j.egyr.2022.11.064

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022, 9-10 December 2021). *Relationship Between Electricity Consumption and Economic Development* International Conference on Electrical, Computer and Energy Technologies (ICECET), Cape Town-South Africa. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9698413

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022b). Sustainable Energy Transition for Renewable and Low Carbon Grid Electricity Generation and Supply [Review]. *Frontiers in Energy Research*, *9*(743114), 1-45. https://doi.org/https://doi.org.10.3389/fenrg.2021.743114

Kabeyi, M. J. B., & Olanrewaju, O. A. (2023). Bagasse Electricity Potential of Conventional Sugarcane Factories. *Journal of Energy*, *2023*, 5749122. https://doi.org/https://doi.org/10.1155/2023/5749122

KPMG. (2022, 9 May 2022). *UK sets out future for carbon pricing*. KPMG. https://home.kpmg/uk/en/home/insights/2022/04/uk-sets-out-future-for-carbon-pricing.html

Lazard. (2019). *Lazard's levelized cost of energy analysis — Version 13.0*. https://www.lazard.com/media/451086/lazards-levelized-cost-of-energy-version-130-vf.pdf

Lazard. (2020). *Lazard's levelized cost of energy analysis — version 14.0*. Lazard. https://www.lazard.com/media/451419/lazards-levelized-cost-of-energy-version-140.pdf

Lazard. (2021). *Lazard's levelized cost of energy analysis — Version 15.0*. Lazard. https://www.lazard.com/media/451881/lazards-levelized-cost-of-energy-version-150-vf.pdf

Lempriere, M. (2022, 09 Feb. 2022). Contracts for Difference auctions to be held annually in 'major step forwards' for net zero transition. *Current*. https://www.current-news.co.uk/news/contracts-for-difference-auctions-to-be-held-annually-in-major-step-forwards-for-net-zero-transition#:~:text=Contracts%20for%20Difference%20(CfD)%20auctions,auction%20rounds%20every%20two%20years.

Müller, K. (2013, 2013.02.01). *Progress in electricity grid expansion*. Bundesnetzagentur. Retrieved 26 January 2023 from https://www.bundesnetzagentur.de/EN/General/contact/contact-node.html

NREL. (2021). *U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021*. https://www.nrel.gov/docs/fy22osti/80694.pdf

NS Energy. (2015). *Bhadla Solar Park, Rajasthan*. Retrieved 23 November 2022 from https://www.nsenergybusiness.com/projects/bhadla-solar-park-rajasthan/

Osborn, D., Cutter, A., & Ullah, F. (2015). *Universal sustainable development goals: Understanding the Transformational Challenge for Developed Countries*. https://sustainabledevelopment.un.org/content/documents/1684SF_-_SDG_Universality_Report_-_May_2015.pdf

Schwartzman, D., & Schwartzman, P. (2013). A Rapid Solar Transition is not only Possible, it is Imperative! *African Journal of Science, Technology, Innovation and Development*, *5*(4), 297-302. https://doi.org/10.1080/20421338.2013.809260

Sklar-Chik, M. D., Brent, A. C., & de Kock, I. H. (2016). Critical review of the levelised cost of energy metric. *South African Journal of Industrial Engineering*, *27*, 124-133. https://doi.org/http://dx.doi.org/10.7166/27-4-1496

The Week. (2019, 12 June 2019). Can the UK reach net zero carbon emissions by 2050? *The Week*. heweek.co.uk/101702/can-the-uk-reach-net-zero-carbon-emissions-by-2050?ppcddm=true&gclid=EAIaIQobChMI_Y-Z_6Lg-wIVEoFQBh2CggOWEAAYAyAAEgK8uPD_BwE

Trinomics. (2022). Energy prices, costs and subsidies and their impact on industry and households. *Trinomics*. https://trinomics.eu/project/energy_prices_costs_and_subsidies_and_their_impact_on_industry_and_households/

U.S. Energy Information Administration. (2022a). *Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2022*. https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf

U.S. Energy Information Administration. (2022b). *Levelized Costs of New Generation Resources in the Annual Energy Outlook 2022*. https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf

UK Government. (2018, 17 July 2018). *Hinkley Point C*. Department for Business, Energy & Industrial Strategy. Retrieved 26 January 2023 from https://www.gov.uk/government/collections/hinkley-point-c

United States Environmental protection Agency. (2022, AUGUST 2, 2022). *Basic Information about NO2*. United States Environmental protection Agency. Retrieved 26 January 2022 from https://www.epa.gov/no2-pollution/basic-information-about-no2#:~:text=Nitrogen%20Dioxide%20(NO2)%20is,from%20the%20burning%20of%20fuel.

Veronese, E., Manzolini, G., & Moser, D. (2021). Improving the traditional levelized cost of electricity approach by including the integration costs in the techno-economic evaluation of future photovoltaic plants. *International Journal of Energy Research*, *2021*(45), 9252–9269. https://doi.org/https://doi.org/10.1002/er.6456

Veronese, E., Manzolini, G., & Moser, D. (2021). Improving the traditional levelized cost of electricity approach by including the integration costs in the techno-economic evaluation of future photovoltaic plants. *45*(6), 9252-9269. https://doi.org/ https://doi.org/10.1002/er.6456

Vitzthum, T. (2013). *Stadtwerke demand gas power plant shutdown*. Welt. Retrieved 23 November 2022 from https://www.welt.de/wirtschaft/energie/article114202846/Stadtwerke-fordern-Gaskraftwerk-Abschaltung.html

Walsh, J. (2017, February 28, 2017). *Protecting Dam Breach Inundation Zones*. Retrieved 21 November 2022 from https://riskandinsurance.com/protecting-dam-breach-inundation-zones/

Authors Biographies

Moses Jeremiah Barasa Kabeyi is currently a doctoral researcher in the Department of Industrial Engineering at Durban University of Technology. He earned his B.Eng. degree in Production Engineering and MSC in Mechanical and Production Engineering (Energy) from Moi University, in Kenya, MA in Project planning and Management from University of Nairobi, in Kenya and Diplomas in Project management, Business management and NGO management respectively from The Kenya Institute of Management. He has worked in various factories including sugar manufacturing at Nzoia Sugar Company Ltd, pulp and paper at Pan African Paper Mills EA Ltd, and power generation at the Kenya Electricity Generating Company (KenGen) in Kenya, in an industrial career of 16 years before moving into teaching. He has taught in various universities in Kenya including University of Nairobi, Technical University of Mombasa, and Egerton University and currently on study leave. His research interests are power generation, fuels and combustion, internal combustion engines and project management and sustainability. He is registered with the Engineers Board of Kenya (EBK) and Institution of Engineers of Kenya (IEK) and has published several journal papers.

Oludolapo Akanni Olanrewaju is currently a Senior Lecturer and Head of Department of Industrial Engineering, Durban University of Technology, South Africa. He earned his BSc in Electrical Electronics Engineering and MSc in Industrial Engineering from the University of Ibadan, Nigeria and his Doctorate in Industrial Engineering from the Tshwane University of Technology, South Africa. He has published journal and conference papers. His research interests are not limited to energy/greenhouse gas analysis/management, life cycle assessment, application of artificial intelligence techniques and 3D Modelling. He is an associate member of the Southern African Institute of Industrial Engineering (SAIIE) and NRF rated researcher in South Africa.