PROJECTIONS OF ELECTRICITY ENERGY MIX CHANGES TOWARDS NEARLY CARBON NEUTRALITY BY 2050

by

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Global electricity consumption reached 28,197 TWh in 2022 and it is expected to rise to 64,513 TWh by 2050, reflecting estimated annual growth rate of 3%. This paper evaluates ten electricity generation technologies—coal, natural gas, hydro, solar photovoltaic, wind, nuclear, geothermal, biomass, biogas, and wave & tidal—each contributing uniquely to global energy production. Despite notable advancements in clean energy technologies, including renewables and nuclear power, global greenhouse gas emissions continue to increase.

The focus of this paper is to propose strategies for constructing new power plants while decommissioning old ones to achieve near carbon neutrality by 2050. Various shares of renewable and nuclear energy in total electricity production are modeled. The analysis examines greenhouse gas emissions, required capacity for each technology, decommissioning costs of old infrastructure, investment requirements for new plants, and land requirements for their construction.

Findings indicate that proposed scenarios are feasible but require more aggressive measures to limit global temperature rise to manageable levels. By simulating diverse strategies, policymakers can better understand potential impacts and make informed decisions regarding necessary changes. Increasing the share of renewable energy, supported by nuclear power, emerges as the primary pathway to achieve carbon neutrality target by 2050.

This analysis adopts a global perspective with a transparent model design that allows easy adaptation to other contexts.

Keywords: *Global Electricity Energy Mix, Near Carbon Neutrality by 2050, Techno-Economic Modeling, Energy System Optimization, Energy Strategy.*

1. Introduction

The Paris Agreement (2015) [1] requires member states to reduce greenhouse gas (GHG) emissions to limit global warming to well below 2°C above pre-industrial levels, with efforts to keep the increase below 1.5°C. The Agreement also aims at carbon neutrality by the end of the century, balancing GHG emissions with absorption by forests and oceans to help stabilize global temperatures.

At the 28th United Nations Climate Change Conference, or Conference of the Parties (COP) [2], scientific discussions emphasize the need to halve emissions by 2030. This conference has provided a pivotal moment to rethink and refocus global climate efforts. The significant outcome is the agreement to triple global renewable energy capacity and to double energy efficiency by 2030, the declaration supported by 130 countries at the beginning of the meeting.

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Since the inaugural COP in 1995 in Berlin, Germany, these conferences have played a pivotal role in fostering global cooperation on climate change. Their primary focus is on mitigating impacts and building a more sustainable and resilient future. COP meetings provide a platform for: (1) negotiating agreements, (2) setting goals and targets, (3) reviewing progress, and (4) sharing knowledge and best practices. While the success of individual COP meetings has varied, COP 21 [1] has specified a milestone by introducing the first clear numerical target for limiting global warming, which is subsequently agreed. However, achieving this target remains uncertain and requires substantial changes in the global energy mix. The transition to a sustainable energy future is complex and slow and progress towards the goal is frequently delayed.

Changes in both national and global energy mix are influenced by political, economic, technological, and environmental factors. The interplay of these factors drives the shift towards more sustainable energy systems, with policies, market dynamics, technological advancements, and environmental considerations shaping the transition.

The primary objective of this paper is to assess technical and economic implications of increasing the share of renewable energy and nuclear energy technologies (RES+Nuc) in the electricity mix, alongside with the integration of Carbon Capture, Utilization, and Storage (CCUS) technologies. The incorporation of CCUS into energy systems can significantly reduce GHG emissions. The analysis includes estimates of land area required for constructing energy plants, investment costs for building new plants, and costs associated with decommissioning outdated facilities.

Key factors analyzed include Capacity Factors (CFs), Operational Reliabilities (ORs), land requirements for new plants, and investment costs—identified as critical parameters for optimizing the energy mix. The model presented in this paper emphasizes simplicity and transparency, distinguishing it from more complex software tools such as MARKAL, MESSAGE, PLEXOS, and EnergyPLAN, which although robust, offer less flexibility for direct influence on independent input parameters.

The paper further differentiates fossil fuel-based technologies (coal and natural gas) and those utilizing renewable or nuclear energy (RES+Nuc). Nuclear energy, as a clean technology, has seen significant advancements, solidifying its critical role in achieving goals outlined in the Paris Agreement.

This paper introduces a straightforward, custom-designed model for optimizing electrical energy systems with the goal of achieving near carbon neutrality. Its defining characteristics include simplicity, transparency, and user control, allowing users to directly manage calculations by adjusting key parameters. These qualities represent the fundamental contributions and uniqueness of this work.

2. Approach and Source of Data

Literature is filled with forecasts of desirable and possible changes in factors determining the energy mix. Some of these forecasts are aspirational, while others provide practical suggestions for achieving desired changes.

The EU Energy Roadmap 2050 [3] represents a significant improvement with reference to energy forecasting compared to earlier studies. It stands out due to several key features:

a. **Long-Term Perspective**: It offers a comprehensive view of energy planning, which extends to 2050.
b. **Integrated Approach**: It considers various components of energy systems—electricity production, transportation, heating, and industrial processes that are interconnected parts thereof.

c. **Technological Diversity**: It explores a broad range of energy technologies and pathways, including renewable energy, energy efficiency, electrification, hydrogen, and CCUS thus providing robust assessment of decarbonization pathways.
d. **Policy Considerations and Regulatory Frameworks**: It emphasizes the importance of supportive policies and regulatory measures in driving transition to low-carbon energy systems, evaluating potential impacts of different policy scenarios.
e. **Stakeholder Engagement**: It incorporates contributions from industry, academia, policymakers, and civil society.

In this way, the EU Energy Roadmap 2050 can be considered as superstructure of previous studies, building upon existing knowledge and integrating latest data, methodologies, and insights to provide forward-looking assessment of the energy future. The Paris Agreement [1], accepted by most countries, implies that governments have to take necessary steps to meet agreed targets while considering their specific circumstances and requirements.

In energy forecasting models, numerous independent variables make models mathematically intricate and prone to errors if physical assumptions are oversimplified or inaccurate. Nevertheless, accurate models provide valuable insights and help policymakers, businesses, and researchers to understand potential trends and to make informed decisions.

To evaluate validity of results from various models, several methods can be used:

a. **Validation against Historical Data**: Models can be compared with past data to assess how accurately they predict historical trends, thereby gauging their reliability in capturing real-world behavior.
b. **Sensitivity Analysis**: By varying input parameters within plausible ranges, analysts can determine how sensitive model outcomes are to these variables. This helps in identifying which factors have the most significant impact on results.
c. **Comparison with other Models**: Running multiple models with different methodologies and assumptions allows a range of possible outcomes. Comparing these results can highlight areas of agreement and divergence and help in identifying uncertainties.
d. **Expert Judgment**: Consultation with experts for the subject can provide valuable insights into plausibility of model results, particularly for complex systems where quantitative models alone cannot capture all relevant factors.
e. **Scenario Analysis**: Instead of predicting a single future outcome, models can explore a range of scenarios under different assumptions. This approach acknowledges the uncertainty in forecasting and helps decision-makers to prepare for various possible futures.

While no model can perfectly predict the future, using these approaches can help in assessing reliability and validity of results from different forecasting models. It is crucial to recognize their limitations while leveraging their strengths to inform decision makers.

This paper employs approaches (a), (d), and (e). Historical data is used to establish initial assumptions and trends (a), while expert judgment based on practical experience [4-6] is used to validate the optimization solution (d). The adopted scenario is based on the analysis of existing similar scenarios (e) [7-9]. Sensitivity analysis (b) and comparison with other models (c) are not conducted because models focused on technical analyses such as this one are not readily available.

There are many institutions that are focused on energy consumption analysis and forecasting. This paper is based on the following eight sources of key data: (1) International Energy Agency (IEA) [10, 11], (2) U.S. Energy Information Administration (EIA) [12], (3) World Energy Council (WEC) [13], (4) International Renewable Energy Agency (IRENA) [14] , (5) Center for Energy and Environmental Policy Research (CEEPR) [15], (6) Carbon Capture and Storage Association (CCSA) [16], (7) Statista [17], and (8) EMBER [18].

These institutions provide critical insights, analyses, and forecasts that shape global energy consumption policies and strategies. Although many other reputable forecasts and data sources exist, the limitation of required space prevents detailed review. Additional sources are listed in references, with special emphasis on studies [19-25].

Finally, planning electricity production portfolio and addressing policy implications—considering costs, emissions, and uncertainties caused by changes—requires careful risk assessment [25]. Rapid and large-scale changes in the electricity mix can threaten environmental quality and complicate decarbonization efforts [10]. Furthermore, fluctuations in fossil fuel prices are frequent and unpredictable, making it crucial to assess their impact on renewable energy consumption [26].

Following thorough analysis of relevant databases and references, limit values of key parameters for all ten technologies are identified. This approach appears to be the most effective way to establish practically usable values for parameters that are critical for this analysis.

Below are summaries of the Capacity Factor (CF), Operational Reliability (OR), and Emission Factor (EF) limit values for examined electricity production technologies. Current values are given, but technological progress will increase CF and OR values and decrease EF in the future.

All tables in chapter 3 are created by analyzing and compiling data from mentioned numerous references and can be considered as a contribution of this paper.

3. Electricity Production Technologies

Tab. 1 presents the analysis of various electricity production technologies, along with their global installed capacities in 2022 [10, 11, 13, 17]. It also provides the share of each technology in the total installed capacity, their contribution to the total estimated annual electricity production (28,197 TWh/y), and the percentage of global GHG emissions attributed to each technology (Total 11,150 $MtCO_2e$ in 2022). The dominance of fossil fuels in electricity production, as well as their significant GHG emissions, is evident.

Table 1. Capacity by Technologies in 2022

	Technology	Installed Capacity[2] (GW)	Share of Total Capacity (%)	Share of Annual Electricity Production (%)	GHG Emissions (%)
1	Coal	2,171	28.65	25.80	61.00
2	Natural Gas	1,933	25.51	28.38	35.88
3	Hydro Energy	1,300	17.15	18.68	1.09
4	Solar Energy (PV)	789	10.41	4.83	0.55
5	Wind Energy	743	9.80	6.92	0.31
6	Nuclear Energy	392	5.17	10.14	0.38
7	Geothermal Energy	156	2.06	3.60	0.25
8	Biomass	75	0.99	1.39	0.44
9	Biogas	18	0.24	0.27	0.10
10	Wave and Tidal Energy	1	0.01	0.00	0.00
	Total	**7,578**			

Installed capacities are the basis of the analysis and based on them, electricity production and GHG emissions will be evaluated. But that will require knowledge of adequate parameters. These parameters include capacity factors (CFs), operational reliabilities (ORs), and emission factors (EFs)

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[2] ***Installed capacity*** *refers to the actual capacity of the plant or facility after it has been constructed and commissioned. It can be equal to or slightly different from the nominal capacity, depending on various factors such as efficiency of equipment, maintenance practices, environmental conditions, and operational constraints. Installed capacity can be determined through testing or monitoring actual performance of the plant in real life conditions.*

Nominal capacity *is rated capacity of the plant or facility as specified by manufacturer.*

as well, and they vary significantly depending on technological advancements and environmental conditions. Although values presented in Tab. 2, 3, and 4 are based on extensive literature review, data have been carefully evaluated.

3.1 Capacity Factor (CF)

The capacity factor measures the efficiency of a power plant, comparing its actual output over a period to its maximum potential if operated at full capacity. Capacity factors vary widely between different plant types, meaning that for the same energy output over a given period, plants with lower capacity factors require higher installed capacity. It is important to note that plant costs are based on nominal capacity, not on actual energy production and real installed capacity.

The indicative range of capacity factors for various technologies is in Tab. 2.

Table 2. Capacity Factors (CFs) for Electricity Production Technologies

Technology	Capacity Factor Range (%)	Average (%)	Notes
Coal	40-50	45.0	Varies depending on plant type and efficiency
Natural Gas	45-60	52.5	Depends on technology and operation conditions
Hydro Energy	30-70	50.0	Varies widely based on water availability and plant design
Solar Energy (PV)	15-30	22.5	Varies depending on location, sunlight availability, and panel efficiency
Wind Energy	30-45	37.5	Depends on wind conditions and turbine technology
Nuclear Energy	85-95	90.0	Consistent high performance
Geothermal Energy	70-95	82.5	Highly reliable due to steady heat source
Biomass	60-80	70.0	Reliable due to consistent biomass supply
Biogas	40-80	60.0	Dependent on feedstock and production consistency
Wave and Tidal Energy	20-45	32.5	Varies depending on location and tidal patterns

3.2 Operational Reliabilities (ORs)

Operational reliability (system security) refers to the plant's ability to generate electricity consistently without interruptions. Below is a summary of average operational reliability for various technologies:

Table 3. Operational Reliabilities (ORs) for Electricity Production Technologies

Technology	Operational Reliability (%)	Average (%)	Notes
Coal	80-90	85.0	Varies depending on plant efficiency and type
Natural Gas	85-95	90.0	Dependent on technology and operation
Hydro Energy	90-95	92.5	High reliability
Solar Energy (PV)	85-90	87.5	Low mechanical failure rates
Wind Energy	70-90	80.0	High durability in modern turbines
Nuclear Energy	90-95	92.5	High reliability
Geothermal Energy	85-95	90.0	Reliable due to constant heat source
Biomass	80-90	85.0	Consistent availability of biomass
Biogas	70-90	80.0	Dependent on biogas production consistency
Wave and Tidal Energy	30-50	40.0	Reliable due to predictable tidal cycles

Data on Capacity Factors (CFs) and Operational Reliabilities (ORs) are generated by an extensive search of numerous databases. For example, on sites [11, 12, 27] there are numerous titles that refer precisely to the values of these parameters. In the paper [29], capacity factors of solar photovoltaic (PV) systems are analyzed in detail. It is certainly better if measured values of these parameters are available for the plants that are the subject of the analysis. In this paper, mean values from the established range will be used, which is sufficient for the analysis of the model at the global level.

To estimate electricity production for a given installed capacity, it is essential to know CFs and ORs for each technology. The formula for calculating annual electricity production is as follows:

$$E(n,a)\left[\frac{GWh}{y}\right] = CF(n)\,[-]\cdot OR(n)\,[-]\cdot P(n,a)\,[GW]\cdot 8760\,[h/y] \qquad (1)$$

Where:

n: Index of electricity production technology (from Tab. 1).
y: Year, ranging from 2022 to 2050.
P(n, y): Installed capacity of the plant in gigawatts (GW).
E(n, y): Annual electricity production in gigawatt-hours per year (GWh/y).

Total electricity capacity grows in line with increased demand, but the share of each technology fluctuates based on energy strategies of different regions or countries. Global energy trends today reflect technological, economic, social, and environmental challenges and opportunities. Many countries are adjusting their energy strategies to align with these trends, leveraging their unique resources and capacities. The major global energy trends include:

a. **Decarbonization and the shift to renewable energy**: Global efforts to reduce carbon emissions aim for "net-zero" by 2050.
b. **Energy transition and renewable integration**: Modernization of grids, development of smart grids, battery storage, and increasing energy storage capacity.
c. **Energy efficiency**: Enhancing the efficient use of energy.
d. **Electrification of transport and heating**: Expanding the use of electricity in sectors traditionally reliant on fossil fuels.
e. **Hydrogen as a future energy source**.
f. **Decentralized energy production**: Consumers becoming producers ("prosumers").
g. **Digitization and smart technologies**: Leveraging technology for energy management.
h. **Geopolitical dynamics and energy security**.
i. **Transition**: Ensuring socially fair shift away from traditional energy sectors.
j. **Climate change adaptation**: Modifying energy systems to cope with impacts of climate change.

These trends influence energy strategies of individual countries and regions, each adapting its goals based on local resources and conditions while striving to align with global sustainability and objectives for reduction of emissions.

This paper illustrates a proposed calculation method using global power plant data (Tab. 1). The same method can be applied to estimate electricity production for any country or region using relevant data. Based on average CF and OR values, global electricity production for 2022 is estimated, as shown in Tab. 4.

Table 4. Global Electricity Production Estimates by Technologies (2022)

Technology	**Installed Capacity**	**Efficiency**	**Capacity Factor (CF)**	**Operational Reliability (OR)**	**Electricity Production**
	GW	**%**	**%**	**%**	**TWh/y**
Coal	2,171	36.5	45.0	85.0	7,274
Natural gas	1,933	55.0	52.5	90.0	8,001
Hydro energy	1,300	90.0	50.0	92.5	5,267
Solar energy (PV)	789	20.0	22.5	87.5	1,361
Wind Energy	743	37.5	37.5	80.0	1,953
Nuclear energy	392	35.0	90.0	92.5	2,859

Geothermal energy	156	15.0	82.5	90.0	1,015
Biomass	75	25.0	70.0	85.0	391
Biogas	18	35.0	60.0	80.0	76
Wave and tidal energy	1	35.0	32.5	40.0	1
TOTAL	**7,578**				**28,197**

In the third column, the average efficiency for each technology is listed, which can be used to estimate input energy requirements [8].

In 2022, global electricity production varied slightly across different data sources but showed consistent trends:

- App. 29,000 TWh (Global electricity generation has increased significantly over the past three decades, rising from less than 12,000 TWh in 1990 to over 29,000 TWh in 2022) [14],
- App. 28,466 TWh (with coal contributing to around 36% or 10,400 TWh, and wind and solar combined accounting for about 12% of global production) [12],
- App. 28,600 TWh (with renewables accounting for around 38%, primarily driven by wind and solar) [10].

The agreement of calculated value (Tab. 4) with these sources is very good.

3.3 Emission Factor (EF)

Since this paper focuses on reducing GHG emissions, it is essential to calculate emission factors for each energy production technology. Emission factors (EFs) for ten technologies discussed are influenced by several factors, including energy efficiency. Tab. 5 presents the range of emission factors for each technology, along with average values used in this analysis [23, 24, 26, 30-32]. The most likely minimum and maximum emission values are derived from extensive reviews of multiple databases referenced in the paper.

Table 5. Emission Factors for Ten Technologies *(These figures reflect lifecycle emissions, including production, construction, and decommissioning, not just operational emissions)*

Technology	Emission Factor (g/kWh)	Average (g/kWh)	Comment
Coal	820-1050	935	Coal capacity has one of the highest emission factors due to high carbon content and inefficient combustion processes.
Natural Gas	450-550	500	Natural gas emits less than coal but still produces significant carbon emissions.
Hydro Energy	1-45	23	Hydroelectric capacity has minimal emissions, primarily from dam construction and maintenance.
Solar Energy (PV)	20-70	45	Solar panels emit no operational emissions; their lifecycle emissions come from manufacturing and installation.
Wind Energy	5-30	17.5	Wind turbines have very low lifecycle emissions, similar to solar capacity.
Nuclear Energy	10-20	15	Nuclear capacity is one of the lowest-carbon options, with emissions mainly from construction, mining, and fuel processing.
Geothermal Energy	5-50	27.5	Geothermal energy has low CO_2 emissions, mostly due to drilling activities.
Biomass	50-200	125	Biomass emissions vary depending on the type of biomass and combustion process.
Biogas	100-200	150	Biogas emits more than other renewables, depending on feedstock and system efficiency.
Wave and Tidal Energy	0-10	5	Still in early development stage, wave and tidal energy produce minimal emissions, primarily from construction.

Carbon Capture, Utilization, and Storage (CCUS) technology has the potential to significantly mitigate global warming and extend the time frame for achieving full decarbonization. The next chapter will explore fundamental characteristics of CCUS, as it is one of crucial components of the model that is being analyzed.

4. Carbon Capture, Usage and Storage (CCUS) Technology

From the data presented so far, the model analyzed here assumes continued use of fossil fuels until 2050 while striving for nearly zero GHG emissions. This goal is only feasible with the integration of CCUS technology, which plays a critical role in mitigating emissions and supporting development of other energy technologies.

Fig.1 illustrates the conceptual role of the CCUS plant within the industrial chain. Many industries rely on fossil fuels or other fuels that release CO_2 and other GHGs during combustion. Instead of allowing these gases to enter the atmosphere, the CCUS technology captures, processes, and stores them to minimize their environmental impact. The CCUS process involves capturing CO_2 emissions from industrial facilities or power plants, transporting captured CO_2 to suitable storage location, and injecting it underground for long-term storage. This will prevent CO_2 from entering the atmosphere and contribute to climate change.

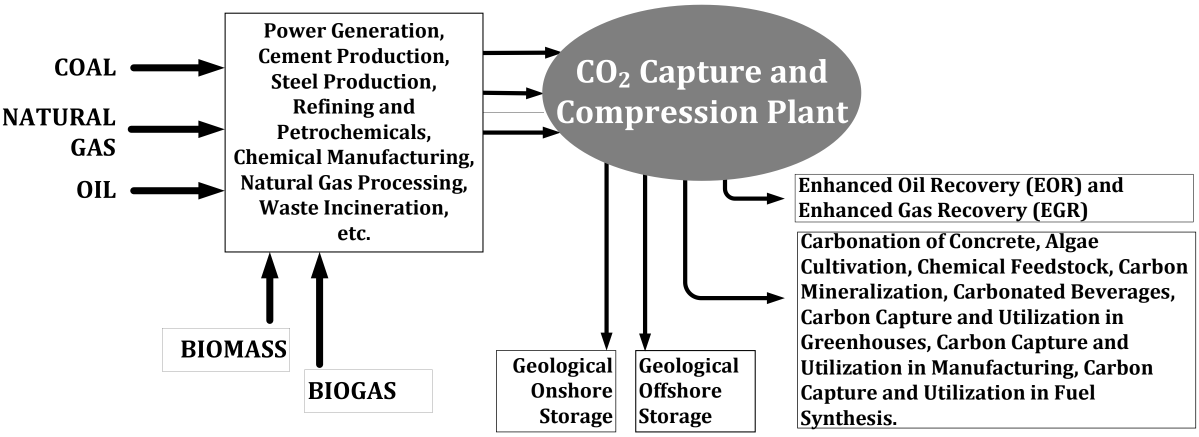

Figure 1. Conceptual Role of the CCUS Plant

CCUS technologies have been developed and implemented worldwide, particularly in regions with significant CO_2 emissions from industries or power production [27, 33-38]. Although CCUS has the potential to play a major role in reducing GHG emissions and combating climate change, its widespread adoption depends on technological improvements, policy support, and economic feasibility [35, 39].

In addition to capturing CO_2, CCUS technologies are being explored to reduce emissions of other potent GHGs such as methane (CH_4), which has a much higher global warming potential than CO_2 over shorter timeframe. Methane is released from sources such as agriculture, oil and gas production, and waste management.

CCUS technologies can be categorized into three main types: **post-combustion**, **pre-combustion**, and **oxy-fuel combustion capture** (Fig. 2) [40].

a. **Post-combustion capture** takes CO_2 from flue gases after fuel combustion.

b. **Pre-combustion capture** involves pre-treatment of fuel with steam and air (or oxygen) to produce syngas (CO and H_2), followed by water-gas shift reaction[3] to convert CO into CO_2 and H_2. CO_2 is then separated, while H_2 can be used as carbon-free energy carrier.
c. **Oxy-fuel combustion** burns fuel in pure oxygen instead of air, producing flue gases primarily consisting of CO_2 and water vapor, which can be easily separated by condensation, yielding highly concentrated CO_2.

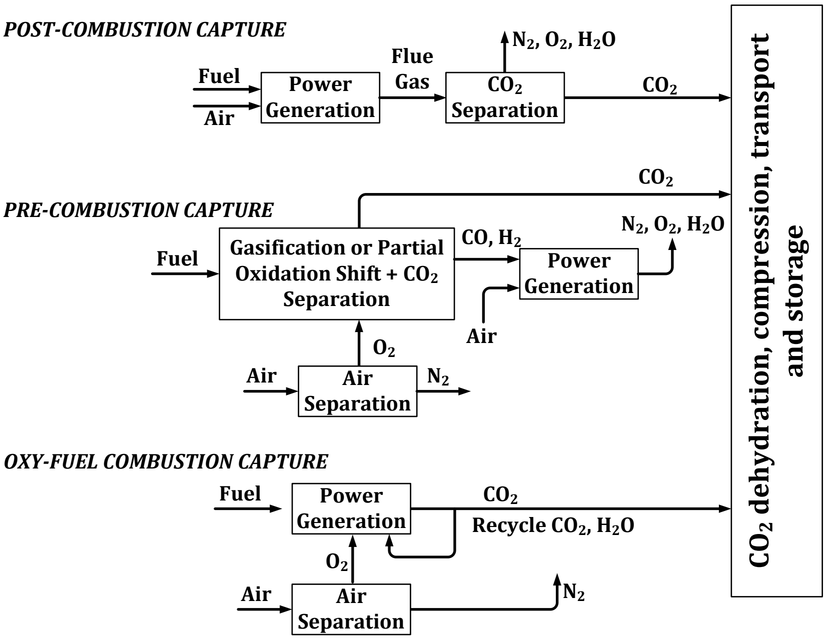

Figure 2. Post-Combustion, Pre-Combustion, and Oxy-Fuel Combustion Capture Technologies

As of 2020, the capacity of CCUS systems has been limited, capturing only a few million tons of CO_2 equivalent ($MtCO_2e$) annually [41-43]. However, forecasts predict that by 2050, CCUS technology could achieve the capacity exceeding 6,000 $MtCO_2e$ per year [42], which is crucial for keeping global temperature rise below 2 °C. To reach this goal, new regulations have to be implemented to incentivize commercial CCUS projects, and governments have to assess and promote carbon storage capacity on a large scale. This is true if fossil fuels remain in use to a significant extent.

The efficiency of CCUS systems is calculated by comparing the amount of CO_2 that is captured, utilized, or stored to the amount that will be emitted without the process. The general formula for CCUS efficiency, which also accounts for CO_2 utilization, is as follows:

$$\text{Efficiency}_{\text{CCUS}} = \frac{CO_2\ captured\ or\ stored + CO_2\ utilized}{Baseline\ CO_2\ emissions} \times 100\% \qquad (2)$$

The efficiency of existing CCUS plants can vary significantly depending on several factors such as specific technology used, plant design, characteristics of CO_2 source, and intended use or storage of captured CO_2. Current data suggest that the efficiency of most CCUS plants ranges from approximately 70% to 90% [42]. On average, this means these plants can capture, store, or utilize between 70% and 90% of CO_2 emissions that will otherwise be released into the atmosphere.

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[3] *Water-Gas Shift (WGS) reaction is a chemical reaction in which carbon monoxide (CO) reacts with water vapor (H_2O) to produce carbon dioxide (CO_2) and hydrogen gas (H_2). The reaction is typically carried out in the presence of a catalyst, often composed of transition metals such as iron, chromium, or copper, supported on various materials.*

5. Methodology

This paper addresses a classic optimization problem involving physical phenomena, where the objective is to find values of independent variables that maximize, minimize, or fit a default value to an objective function, while adhering to certain constraints.

The objective function links independent variables that determine the share of renewable energy sources and nuclear capacity (RES+Nuc) in the electricity mix. Independent variables refer to years within the interval [2022–2050] and 10 selected electricity production technologies. The nonlinear objective function is expressed as follows:

$$\phi[P(n,\tau), E(n,y), CF(n), OR(n), EF(n), SLA(n), SIC(n)] = M \text{ (Default value)} \tag{3}$$

Where:

n: Index of electricity production technology (from Tab. 1)
y: Year, from 2022 to 2050
$P(n, y)$: Installed capacity of the plant [GW]
$E(n, y)$: Annual electricity production [TWh/y]
$CF(n)$: Capacity factor [%] (Tab. 2)
$OR(n)$: Operational reliability [%] (Tab. 3)
$EF(n)$: Emission factor (Tab. 5)
$SLA(n)$: Specific land area [km^2/GWe] (Tab. 6 and 7)
$SIC(n)$: Specific investment cost [MEur/MWe] (Tab. 8)

The parameter M *[%]* is set within the range [40–100], defined by the following equation:

$$M[\%] = \left(\sum_{n=3}^{10} P(n, 2050) \middle/ \sum_{n=1}^{10} P(n, 2050) \right) \times 100 \tag{4}$$

This equation predetermines the share of installed capacity from RES+Nuc in the total installed capacity in 2050. The annual percentage of capacity change for each of technologies is subject to optimization. The task is to adjust the annual percentage share of each technology to achieve desired electricity production in 2050.

By increasing the share of RES+Nuc at the expense of fossil fuel-based technologies, GHG emissions can be significantly reduced, which is the primary goal. Achieving this target requires investments in new plants and decommissioning of existing ones causing changes in land area occupied by energy production facilities.

The key to solving such complex optimization problems lies in the correct selection of initial parameters, use of advanced algorithms and techniques to find global solutions, and careful verification of results through multiple methods. Additionally, it is essential to consider factors such as available natural resources, economic conditions, scientific and industrial capabilities, and public awareness to prevent global warming. These factors will determine the pace of planned changes and should be integrated into overall energy strategy.

In this paper, electricity production is projected to grow at an annual rate of 3%, starting from 28,197 TWh in 2022 (Tab. 4) and reaching 64,513 TWh by 2050. This projection serves as the default value for the presented model. Fig. 3 illustrates global primary energy and electricity production from 2022 to 2050 under different annual growth scenarios.

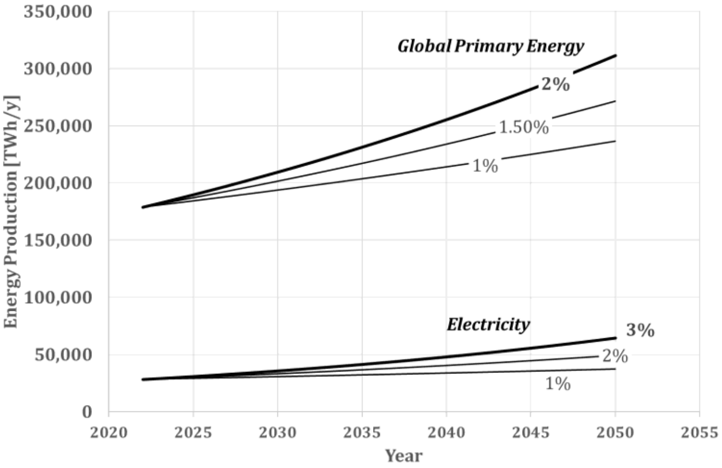

Figure 3. Global Primary Energy and Electricity Production (2022–2050)

Various sources in literature offer different growth forecasts for both primary energy and electricity. After careful review of these sources [14, 43], we have adopted 3% growth rate for electricity production.

The optimization process is conducted using MS Excel Solver and VBA tools (Generalized Reduced Gradient nonlinear method is used). The following parameters are considered:

a. For each technology, it is necessary to define planned and expected range of annual percentage change of plant capacity. That scope has to be in full agreement with the energy strategy and has to reflect intentions and possibilities for their realization. The optimization is also performed assuming that the objective function is M [%] (Default Value) (Eq. 3) and that the total electricity produced in 2050 is as follows:

$$\sum_{n=1}^{10} E(n, 2050) = Default\ Value \tag{5}$$

If there is no solution, it means that planned ranges of capacity changes by individual technologies are not realistic and that they have to be adjusted to requirements (M and $\sum_{n=1}^{10} E(n, 2050)$).

These percentage ranges reflect general trends but can vary by region and over time due to factors such as policy changes, technological breakthroughs, and economic conditions. Although percentages are determined based on detailed analysis, they are subject to scrutiny and further refinement.

For example, the decrease of 1% in electricity energy mix from hydro energy by 2050 can be attributed to several factors, including:

- **Environmental Concerns**: New regulations concerning environmental impacts of hydroelectric projects can lead to favoring less ecologically invasive energy sources, such as solar and wind [44].
- **Limited Growth Potential**: In many regions, geographic constraints and community opposition hinder new hydroelectric projects, limiting expansion opportunities.
- **Technological Advancements**: As solar, wind, and other renewable energy technologies are becoming more cost-effective and efficient, they can take market share from hydroelectricity.

- **Climate Change**: Changing precipitation patterns due to climate change can reduce water availability and decrease reliability of hydroelectric plants.
- **Economic Factors**: High maintenance and upgrading costs of hydroelectric infrastructure can lead to reduced investments, especially compared to cheaper renewable options such as solar and wind.

This paper analyzes the growth in the share of renewable energy sources and nuclear capacity within closed interval [40 (10) 100] %. Such a broad range requires adjusting constraints in certain calculations since ensuring convergence under specified conditions is not always possible. Naturally, expanding limits of constraints too much will lead to unrealistic solutions.

According to data from the International Renewable Energy Agency (IRENA) [14], the global potential for solar PV is substantial. IRENA estimates that by 2050, technical potential for solar PV installations worldwide can range from 49,000 to 76,000 TWh annually. Based on the comprehensive review of literature, maximum share of solar PV in global electricity production is assumed to be 20% reaching around 10,630 TWh by 2050. However, this figure is significantly lower than IRENA projections, which exceed expected global electricity production. It should be said that some developed countries plan and achieve significantly higher share of solar PV of 20%.

b. The total CCUS capacity measured in $MtCO_2e$ is calculated annually starting from 2022 when the capacity was approximately 200 $MtCO_2e$. The goal is for annual increase in CCUS capacity to meet requirements of all fossil-fuel-based plants (coal and natural gas) by 2050. Each of these plants, whether existing or future, will reduce GHG emissions under the assumption that CCUS technologies will be utilized, and GHG emissions:

$$GHG = \sum_{n=1}^{2} \sum_{y=2022}^{2050} EF(n) \cdot E(n,y) \tag{6}$$

will be minimized to technical limit.

c. Different technologies require varying amounts of land per unit of produced electricity. The assessment is made based on available data and using the average land area required per kWe of output capacity.

For all ten technologies, the analysis has determined approximate land area requirements per kWe of output from the plants (Tab. 6). Due to limited data in literature, estimates are based on project documentation from several known projects [45], and different reports from [11, 12, 46-49].

Table 6. Approximate Land Area per kWe of Output for Various Technologies

Technology	**Average Values km^2/GWe**
Coal-Fired Plants: Estimated area is 5–10 km²/GWe. Key factors include coal storage, plant facilities, ash disposal, cooling systems, and infrastructure for fuel delivery.	7.5
Natural Gas-Fired Plants: Estimated area is 1–3 km²/GWe. While less fuel storage is needed compared to coal, gas storage and transport infrastructure are still required. Combined cycle plants can need additional space for cooling systems.	1.5
Hydro Plants: Estimated area is 10–250 km²/GWe largely depending on the size of the dam and reservoir. Dams, reservoirs, and spillways occupy vast areas although run-of-river plants require much less land typically 1–5 km²/GWe since they primarily consist of mechanical and electrical components.	3.0
Solar Plants (PV): Estimated area is 20–40 km²/GWe. Solar panels, inverter stations, and space for	30

maintenance access are key factors. Typically, no fuel storage or waste disposal is required.	
Wind Plants: Estimated area of 5–10 km²/GWe is required for turbine footprint but spacing for wind farms can increase the total area to 50–100 km²/GWe. Large spacing between turbines is needed to minimize wake interference.	75
Nuclear Plants: Estimated area is 5–10 km²/GWe. Factors include large infrastructure for the reactor, fuel storage, cooling systems, safety systems, and waste management facilities.	7.5
Geothermal Plants: Estimated area is 1-5 km²/GWe. Although plants have relatively small footprint, the area can expand slightly due to well-drilling and steam fields.	3
Biomass Plants: Estimated area is 3–10 km²/GWe. Key contributors to the footprint include biomass storage, handling facilities, boilers, and cooling systems.	6.5
Biogas Plants: Estimated area is 2–8 km²/GWe. The footprint includes space for digesters, biogas storage, and gas engines.	5.0
Wave and Tidal Energy: Estimated area is 10–30 km²/GWe. Depending on technology (wave or tidal), the footprint is primarily due to submerged or semi-submerged structures and onshore conversion equipment.	20.0

The required land area for CCUS plants is based on their annual carbon absorption capacity (Tab. 7).

Table 7. Approximate Land Requirements for CCUS Plants

Capacity of CCUS Technology	Used Value of Land Area $m^2/(tCO_2e/y)$
The gross area required for storing 1 ton of CO_2 equivalent in the CCUS plant can be roughly in the range from 0.1 to 0.5 m² per tCO_2e/y	0.5

Data in Tab. 6 and 7 are certainly subject to criticism because they are based on a limited sample and should be understood as such.

d. Investments in new plants to meet electricity demand according to the analyzed model are the most variable part of calculations. They are subject to continuous revisions based on local conditions. Tab. 8 provides rough estimates of investment costs for plant construction by technology. In addition to new plant construction up to 2050, some plants will be decommissioned, which incurs costs. These decommissioning costs are given as the percentage of construction costs. Average values are used for calculations.

Table 8. Specific Investment and Decommissioning Costs for Various Technologies

Technology	Investment Range (Million EUR/MWe)	Average (Million EUR/MWe)	Decommissioning Cost (%)	Average Decommissioning Cost (%)
Coal	2–3.5	2.75	10–30%	20.0
Natural Gas	0.8–1.5	1.16	5–15%	10.0
Hydro Energy	1–3	2.00	10–20%	15.0
Solar Energy (PV)	1–2.5	1.75	5–10%	20.0
Wind Energy (Onshore/Offshore)	1.2–2.5 (Onshore) 2.5–4.5 (Offshore)	2.85	10–20% (Onshore) 15–30% (Offshore)	20.0
Nuclear Energy	3–6	4.50	15–30%	22.5
Geothermal Energy	2.5–5	3.75	10–20%	15.0
Biomass	2–4	3.00	10–20%	15.0
Biogas	1–3	2.00	10–15%	12.5
Wave and Tidal Energy	4–8	6.00	15–25%	20.0

These ranges provide a general understanding of investment costs associated with each technology. It is important to consider significant variability of all project-specific factors, global technological advancements, and market conditions [17, 39, 42, 43, 50].

Costs of CCUS plants vary considerably in the range from around 30 to 250 EUR per tCO_2/y depending on the complexity of involved processes (capture, transport, and storage). In this paper, the cost of 150 EUR per tCO_2/y is assumed [17, 42, 51, 52].

6. Results and Discussion

Estimates of global electricity production for the year 2050 are determined using the following calculations:

- Capacity of plants using fossil fuels compared to those relying on renewable sources and nuclear energy.
- Total global electricity production and consumption is projected to reach 64,513 TWh/year by 2050.
- Electricity production from renewable sources and nuclear energy modeled for different shares of RES+Nuc energy in the electricity mix, ranging from 40% to 100%.
- GHG emissions are estimated both with and without the use of CCUS technologies.
- Changes in above-ground land area due to construction of new plants and decommissioning of old ones.
- Investment costs for building new plants and decommissioning those that are no longer in use.
- Required upgrades to CCUS capacity by 2050.

Fig. 4 illustrates electricity production and how it depends on the share of RES+Nuc energy in the total electricity production. Adequate installed plant capacities are also shown.

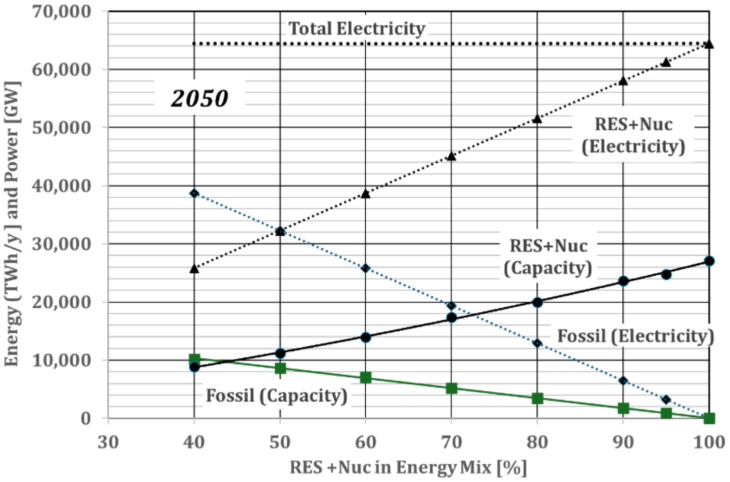

Figure 4. Electricity Production and Capacity of Plants in 2050

Total global installed capacity of plants in 2050 will increase 2.42 times for M=40% and even 3.55 for M=100% compared to 2022. The reason is small CFs and ORs of renewable energy technologies compared to those that use fossil fuels.

Fig. 5 shows GHG emissions for scenarios where CCUS technologies are applied and where they are not used in fossil fuel plants (coal and natural gas). The role of CCUS is highly instructive, but whether it will be deployed depends on several factors discussed earlier. The efficiency of the CCUS system is taken to be 80% (Eq. 2).

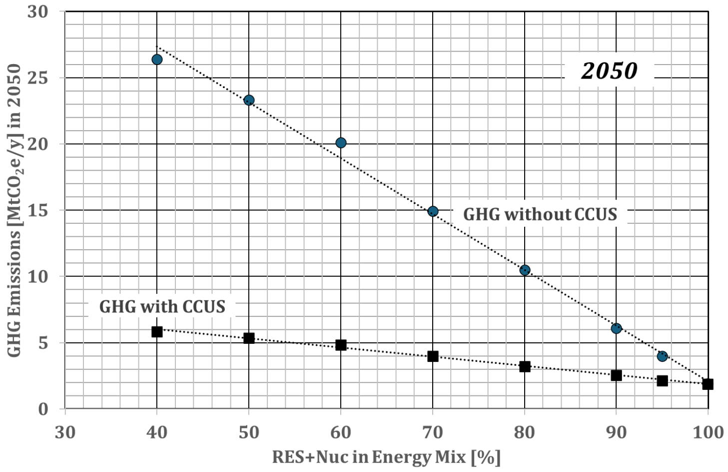

Figure 5. GHG Emissions with and without CCUS Technologies

Fig. 6 presents changes in investment costs and required land area for building new plants with different shares of RES+Nuc energy in the mix until 2050. Investment costs are estimated using rough assumptions based on current prices, which limits absolute precision of results. However, in relative terms, results remain convincing. The required land area increases significantly with the adoption of solar PV and wind technologies.

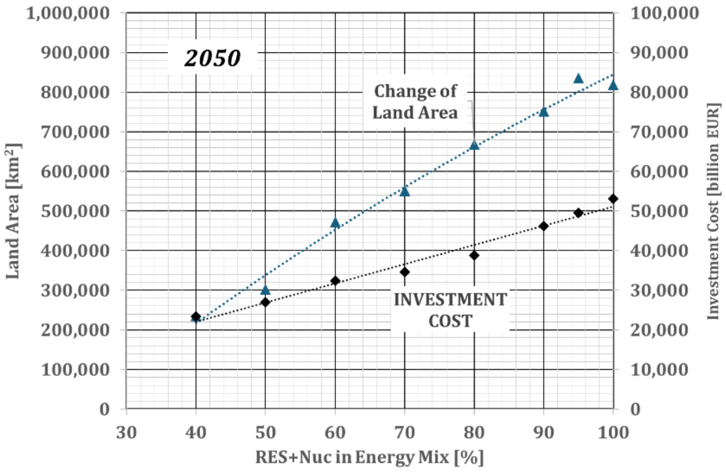

Figure 6. Investment Costs and Required Land Area for New Plants

This paper provides global calculation of electricity production. It is unlikely that all fossil fuel plants will be closed by 2050, but with optimism, the scenario in which 90% of electricity comes from RES+Nuc (M = 90%) is considered achievable. Tab. 9 shows installed capacity (in GWe) by technologies for years 2022, 2030, 2040, and 2050 along with annual percentage change (shown in the grey row). The rapid growth of solar PV and wind capacity is evident, along with significant reduction of fossil fuel plants.

It remains an open question whether national economies are able to implement such an ambitious plan.

Table 9. Plant Capacity Change for M = 90% Scenario

Year	Coal	Natural gas	Hydro energy	Solar energy (PV)	Wind Energy	Nuclear energy	Geothermal energy	Biomass	Biogas	Wave & Tidal energy
%	-3.32	-2.79	0.87	9.87	9.78	1.00	1.00	1.00	1.00	1.00
2022	2,171	1,933	1,300	789	743	392	156	75	18	1.00
2030	1,657	1,542	1,393	1,675	1,568	424	169	81	19	1.08
2040	1,182	1,162	1,518	4,295	3,986	469	187	90	22	1.20
2050	843	876	1,655	11,009	10,135	518	206	99	24	1.32

Fig. 7 highlights the global annual growth rate of CCUS capacity and expected CCUS capacity in 2050 for various shares of RES+Nuc in the electricity mix.

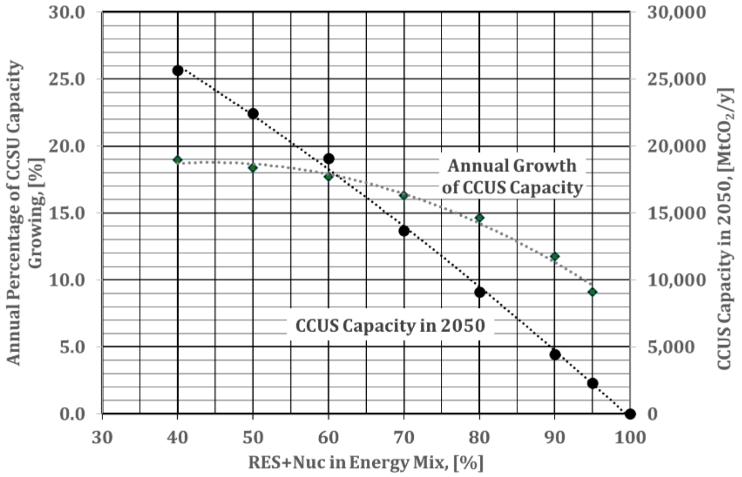

Figure 7. Global CCUS Capacity and Growth Rate by 2050

7. Conclusions and Policy Implications

The model presented in this paper is transparent and has been tested with global data. It can be easily adapted to other regions or entities, allowing for the incorporation of their specific characteristics. The comprehensive overview of parameters for all ten electricity production technologies is provided, recognizing that these parameters will evolve as technologies improve, thereby affecting future outcomes.

The ultimate objective is to create conditions that enable near carbon neutrality by 2050. Among analyzed technologies, solar PV and wind capacity have proven to be the most viable, though significant contributions are also expected from CCUS plants and nuclear energy.

The International Energy Agency (IEA [11] has reported a significant rise in global GHG emissions, increasing from 9.3 $GtCO_2e$ in 1990 to 14.6 $GtCO_2e$ in 2022. This surge is largely attributed to growing electricity demand and to limited integration of renewable energy sources and nuclear capacities.

According to calculations in this paper, if RES and nuclear energy account for 90% of total electricity production by 2050, GHG emissions can be reduced to 6.3 $GtCO_2e$ without CCUS and to as low as 2.6 $GtCO_2e$ with CCUS implementation. Although current technologies make this feasible, there are still concerns about the ability of global economies to effectively implement such changes.

From a technical standpoint, there is considerable potential to limit and control anthropogenic impact on global warming. However, energy policies need to evolve more dynamically and reflect political, economic, technological, and environmental factors for these goals to be achieved.

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