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Gas Turbine's share in the future electricity system, under the effect of EU ETS policies

A Modeling of the future energy transition, considering CO_2 reduction policies by European ETS.

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MASTER'S THESIS IN SUSTAINABLE ENERGY SYSTEMS

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List of Acronyms

The List of acronyms that have been used throughout this study in alphabetical order:

CC: Combined cycle
CCPP: Combined cycle power generation plant
CCU: Carbon capture and utilization
CCS: Carbon capture and storage
Cg: Power generation with cogeneration of heat
CH4 dec: Natural gas with decarbonization technology
CH4 CCS: Natural gas fuel and carbon capture technology
C-cost: Carbon cost
CO_2: Carbon dioxide
CS: Carbon storage
Dec: Decarbonization
EEA: European Environment Agency
EU ETS: European Union emission trading system.
EU4: Nuclear power plant
EUR: Europe
GAMS: General algebraic modeling system
GET: Global energy transition
GHG: Greenhouse gas emissions
GT: Gas turbine
H2: Hydrogen
HRSG: Heat recovery steam generator
IEA: International Energy Agency
KWh: Kilo Watt-hour
LF: Load factor of power plant
Mt CO_2e: Million tons of carbon dioxide equivalent.
NG: Natural gas
NZY: Net Zero Year
RES: Renewable energy systems (in this study, only solar and wind)
SC: Simple cycle
SCPP: Simple cycle power generation plant
TWh: Tera Watt-hour

Nomenclature

η_{overal}	Power plant overall efficiency (electricity and heat)
η_{El}	Power plant electrical efficiency (gas and steam turbines)
$PowerEl_{out}$	Generator electricity output
$Heat_{out}$	Plant heat output
Q_{fuel}	Plant (GT) input energy, fuel energy content

Abstract

Power generation plays a significant role in global warming, as it is a primary source responsible for emitting a substantial amount of harmful greenhouse gas (GHG) pollutants into the atmosphere, and this topic presents a critical and concerning problem on a global scale [1]. As part of implemented actions against global warming, the European Emission Trading System (EU ETS) is a functioning mechanism managing European emission reduction policies [2]. On the other hand, using gas turbines (GT) in power generation, specifically with natural gas, has been a well-established method for converting fuel to electricity. The primary objective of this study is to identify the future share of gas turbine application in the electricity production market (considering the SGT-800 gas turbine, a mid-range Siemens Energy product) under the effect of EU ETS possible scenarios. In addition, possible sustainable solutions for gas turbine applications, specifically hydrogen (H2) as a carbon-free fuel and carbon capture system (CCS), are under consideration. By modeling various potential scenarios and analyzing the outcomes and trends, the study will shed light on how gas turbine market share and competitiveness might be affected in the future. Emission CAP, carbon cost, and Net Zero target year represent EU ETS policies. In addition to EU ETS measures, some techno-economical items have been considered, consisting of power generation modes for gas turbines (simple and combined cycles), which determines the efficiency of electrical generation plants, investment and operation costs, available carbon storage capacities, and different shares of renewable energy systems (RES) in electricity production. The cost of fuels and phasing out old technologies (nuclear and fossil fuels including coal and oil) [3] will be considered technical parameters and, simultaneously, could be complementary policies in different scenarios. The global energy transition (GET) model generates the solutions with the lowest cost for future electricity mix under various technology assumptions and CO_2 emission constraints. Results revealed a significant role of emission CAP, in parallel with a proper carbon cost. At the same time, CO_2 storage capacity and penetration of RES in the electricity market also have considerable effects on gas turbine application. Based on different scenario outcomes, hydrogen(H2) as a carbon-free fuel for GT and CO_2-capturing technology in power plants are effective solutions for integrating gas turbine-based power plants in a more sustainable future energy system.

Keywords:

EU ETS, electricity market, Gas Turbine, Power generation, hydrogen fuel, Carbon capture

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1. Introduction

Global warming and climate change are the most essential and critical environmental concerns in recent decades. Greenhouse gas emissions (GHG), especially carbon dioxide (CO_2) emissions, are responsible and the leading cause of global warming and climate change [2]. Since the severity of these issues became apparent, researchers, policymakers, and the public began to take notice, and numerous global conferences were organized to address these issues. Fossil fuel combustion and human activities are the primary sources of GHG, where CO_2 emissions account for 76% of global GHG. Emissions from the energy sector are the most significant contributors to CO_2, accounting for up to 80% of the total global CO_2 emission; meanwhile, electricity generation is responsible for the largest share (42%), followed by transportation and industry [2]. During the different phases of EU ETS and before, the stationary energy sector (electricity and heat production) has been the highest contributor to global CO_2 emissions [4]; consequently, using primary fossil fuels like coal, oil, and natural gas in electricity generation has garnered significant attention from governments and researchers. Policymakers have introduced various agreements and measures to address this issue.

This study investigates the EU ETS system as a functioning mechanism in Europe and explores potential future scenarios. It examines how different measures and policies may influence gas Turbines' (GT) future market share and competitiveness in the European electricity power generation sector. During the study, the SGT-800 model, a medium-range gas turbine product by Siemens Energy AB, has been considered a typical GT for modeling and simulation purposes. During the study, a linear optimization modeling tool (GAMS) was used to calculate future scenarios in the electricity market technology mix, having different policies and technical items as the main affecting inputs in a Global Energy Transition modeling script (GET) developed by Chalmers University of Technology. Outcomes have been used to determine the future share of gas turbine application in power generation and the share of sustainable possible solutions for gas turbines under the effect of EU ETS policies. Study outputs could be used by policymakers, investors, power plant operators, and turbine manufacturers to support their decisions about achieving and adopting a future carbon-free energy market.

2. Aim of the Study

This study aims to consider potential scenarios for the EU ETS policies and how they will influence the development of the energy sector in Europe and, as a more specific goal, the possible share of gas turbine power generation in the future electricity production technology mix. Meanwhile, applicable sustainable solutions for electricity production using GT technology have been considered in this study. A modeling tool based on the target of reducing emissions with the most cost-effective method was used in this study.

In addition to gaining an overall understanding of the gas turbine's share in the future energy market under the effect of EU ETS policies -and other technical factors- the findings and trends can be used to provide insight into solutions for electricity production by the gas turbine in the energy industries, providing possible ways of lowering carbon footprint by gas turbine technology and attain long-term sustainability goals in line with the Paris Agreement.

2.1. Problem Description

Based on the green transition, the following decades are a time for transforming the energy market towards more sustainable electricity production and moving away from fossil fuels. The importance of the current policies and trends towards a more sustainable future -with less GHG emissions- reveals challenging limitations for applying fossil fuel consumer technologies -as main GHG emitters [2]- in the future. Although the combustion of natural gas in gas turbines has less emission than coal and oil, more research and technical developments are still required. An over-arching target for the gas turbine business is to make gas turbine applications more sustainable. This can be achieved by integrating the technology into the future sustainable energy system, making it compatible with renewable sources, and offering large-scale electricity-producing technology without dependence on fossil fuels. Sustainable power production by gas turbines makes it possible to use the advantages of this technology, namely short ramping up time, fast return of investment, and capability of burning carbon-free gaseous fuels (hydrogen and biofuels)as well as being independent of weather such as sun and wind profiles; at the same time, it could meet the World Energy Council's trilemma of secure, affordable, and environmentally sustainable energy [6]. By evaluating gas turbines' role in the future electricity market under the effect of EU ETS policies, it would be possible for both GT producers and power plant investors to plan for the next decades regarding the application of gas turbines and using their advantages in the energy system.

2.2. Aim and Study Questions

As the aim of this study, modeling of energy transition in the future (up to 2100) will be implemented. The primary outcomes to be evaluated include the share of gas turbines in the future energy mix, while different scenarios, such as EU ETS policies to decrease global warming, would affect the results (such as emission CAP, Net Zero target year, and carbon cost/tax). In addition to EU ETS policies, various technical and market parameters will be considered during the modeling process, including power production efficiency, fuel availability and price, renewable share, CO_2 storage capacity, and phasing out nuclear and coal/oil power generation. Analyzing the modeling results will help better understand future trends for different fuels, energy sources, and technologies in electricity production systems and how their application would increase -or decrease- based on the target of reaching Net Zero emission, given the model's prerequisites and the sensitivity analysis. One primary assumption in this study is that the conversion of gas fuels, mainly NG and hydrogen, to electricity, is performed in a gas turbine (or at least could be the potential of gas turbine application); this idea would provide insight for determining the potential share of the gas turbines in the electricity production in the EU considering electricity production from NG and H2 as application and share of GT in the electricity market. This study seeks to assess the viability of hydrogen as a carbon-free fuel for gas turbines. Natural gas as the main current fuel for gas turbines could be an option for replacing and phasing out coal and oil-based electricity. Additionally, the research will assess the need for implementing CCS as a complementary measure for gas turbine power generation, using either natural gas or electro-fuels[1].

The findings of this research will provide valuable insights into the potential future of the energy industry, with a specific focus on the utilization of gas turbines and the incorporation of more sustainable and environmentally friendly technologies under reforms by EU ETS policy and instruments. Ultimately, the study aims to inform policymakers and industry stakeholders about future pathways for the EU ETS and gas turbines' role in achieving a sustainable, low-carbon energy future. This study tried to find answers to two critical questions regarding the future of gas turbines considering policies and instruments in EU ETS.

1- *What is the share of gas turbine technology in the future electricity production market under the influence of emission reduction policies in the EU ETS?*

2- *Which sustainable solutions are feasible for gas turbine power production in the future electricity market, considering the influence of the EU ETS?*

[1] Electrofuels are synthetic fuels produced from electricity, water, and CO2, which can be formed into almost any hydrocarbon or alcohol fuel, e.g., electro-methane, electro-methanol, electro-diesel, and so on. For GTs, it is first and foremost electro-methane that is of interest, but it is also possible to use other types of electrofuels.

2.3. Delimitation

This study focuses on the power generation sector (electricity market), using GT as the primary technology for converting gaseous fuels (NG and hydrogen) to electricity in Europe, under the effect of EU ETS policies. The time frame for the study is between 2030 to 2100. As possible EU ETS measures, input variables are carbon cost, emission CAP, and Net Zero target year. The central part of the modeling outputs used for results analysis is electricity production share, converting natural gas (NG with and without carbon capture) and hydrogen to electricity.

While an essential aspect of energy systems modeling is the impact of policies and regulations on the energy sector, such as the European Union's measures to follow the Paris Agreement and reduce GHG [5], some critical technological and market parameters were used as variable inputs for modeling, such as power production efficiency, fuel types and fuel cost, wind and solar energy (RES) penetration in the market (based on their CAPEX), and available carbon storage capacities are considered as input parameters.

3. Background and Literature Study

To address the growing concerns regarding global warming and the dangerous effects of GHG, various mechanisms have been developed worldwide to control their emission. The Paris Agreement has been established based on a nationally determined contribution towards the global decrease of GHG emissions [7]. Many countries decided to introduce or expand a domestic CAP-and-trade market for GHG emissions. The EU ETS represents a well-established mechanism for addressing the environmental challenges associated with traditional energy systems [7]. On the other hand, the electricity and heat generation sectors are significant sources of GHG emissions, and the International Energy Agency (IEA) has underscored its role in contributing to these emissions. According to the IEA's Global Energy CO_2 Status Reports, these sectors are crucial in GHG emissions [8]. In the IEA 2021 report, it is mentioned that the electricity and heat production sector is the most significant emitter of CO_2, with an increase of over 900 Mt globally. This sector contributed to 46% of the global rise in emissions, as the utilization of all fossil fuels increased to fulfill the growing electricity demand [8]. Consequently, CO_2 emissions from the electricity sector reached nearly 14.6 Gt, the highest ever recorded level and around 500 Mt more than 2019 [8].

3.1. European Emission Trading System (EU ETS)

EU ETS was established in 2005 in 4 primary phases as a vital instrument of the EU's climate policy to combat climate change by reducing emissions cost-effectively; it covers approximately 40% of Europe's total emissions from installations and companies in the electricity and heat production, energy-intensive industry, and aviation sectors [9]. The EU ETS is currently in the fourth phase of its operation (2021-2030), and the most recent revision of the relevant directive covers 2024-2030 [9]. The decisions introduced in this revision are expected to contribute to achieving both the overall climate target for 2030 and the longer-term climate neutrality target for 2050 [9]. The latest revised system includes several significant changes, such as introducing tighter emissions limits in the form of emission CAP and an innovation fund to support the development of low-carbon technologies [10]. These changes are designed to help the EU meet its ambitious climate goals under the Paris Agreement, with a target for limiting global warming to well below 1.5 °C above pre-industrial levels [10]. In 2021, the EU ETS included 12,146 stationary installations within various industrial sectors and applies to all combustion installations with a capacity greater than 20 MW in 31 countries [8]. The GHG emissions of all stationary facilities covered by the EU ETS in 2021 were 1,331 Mt CO_2e. The stationary installations falling under the EU ETS were categorized into eight primary groups according to the main activities that generate GHG emissions [11]. At the same time, this study focuses on the power generation sector and, more specifically, the electricity market.

3.1.1. CAP, Allowances, Emission Price

The EU ETS operates on a CAP-and-trade system; it imposes a limit, or "CAP," on the total volume of GHG emitted by power plants, industrial factories, and the aviation sector. This CAP is achieved by granting only a certain number of emission allowances. Companies can receive these allowances or purchase them as needed [10]. Over time, the CAP is gradually reduced each year, ensuring a decrease in total emissions, and encouraging investment in low-carbon technologies [10]. The European Union establishes an annual declining limit on CO_2 emissions, requiring companies to possess European Emission Allowances (EUAs) for every ton of CO_2 released annually. These permits are acquired or purchased and can be traded. At the end of each year, companies must gather enough allowances to offset their total emissions [12]. With the EU ETS, the European Union has made a market mechanism for trading the allowances; this gives CO_2 a price and creates incentives to reduce emissions cost-effectively [12]. The goal is to decrease emissions in power generation and other energy-intensive industries. Under the scheme, companies must buy or receive allowances corresponding to their CO_2 emissions; as a result, it leads to increased costs for generating power through the combustion of coal and other fossil fuels while simultaneously making carbon-free energy sources comparatively more appealing [12]. *Figure 1* demonstrates the allowance and actual emissions in the EU from 2005.

The EU ETS reforms -completed in December 2022- guarantee that carbon costs will remain very high throughout the 4th phase of the EU ETS, which ends in 2030 [9]. Together with the phasing-out of free allowances to industry, they are expected to drive down emissions from EU ETS sectors further [9]. The latest revision of the EU ETS has introduced more rapid reductions in the maximum annual quantity of available allowances and imposed additional restrictions on the supply of allowances in the market [9]. These measures aim to achieve a 62% reduction in emissions from the electricity and heat production and energy-intensive industry sectors covered by the EU ETS by 2030, compared to 2005 levels [9]. In addition to the emission trading market, based on the CAP and allowances system, another direct method that policymakers could use is putting a price as tax for each tone of carbon emission. A carbon tax could decrease emissions, increase energy saving, or substitute fuels [13]. This method could determine a price, not as a part of market interactions under the effect of limited allowances but as a direct control tool for different sectors. However, a direct tax will increase the total cost of high-pollutant sections. A carbon tax could be invested in some sections, such as schools or hospitals, while the money from allowance will be circulated among industrial actors, making it easier for industries to accept CAP instead of direct tax for emissions.

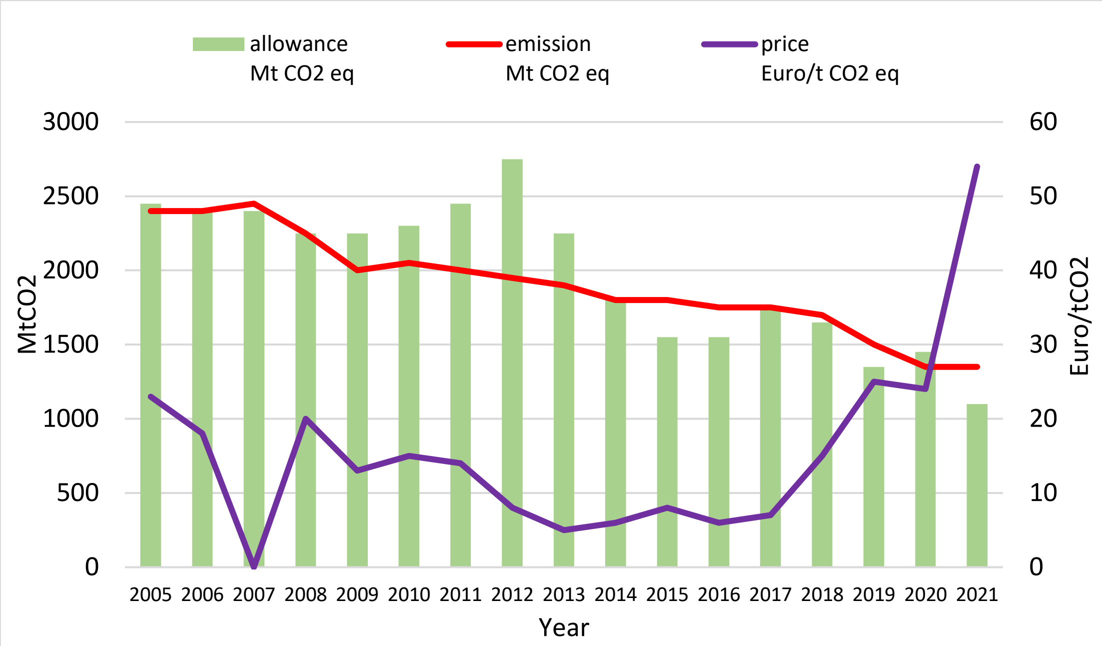

Figure 1. Emission, allowance, and allowance price in the EU 2005 - 2021 [10].

3.1.2. New Target in EU ETS, Fit for 55

The European climate law establishes the realization of the EU's climate objective, which entails a reduction of EU emissions by at least 55% by the year 2030. EU countries are pursuing this goal through new legislation and making the EU climate-neutral by 2050 [14]. As of July 14, 2021, the European Commission embraced a set of legislative proposals known as "Fit for 55" as a crucial aspect of the European Green Deal, intending to enhance the European Union's role as a frontrunner in global climate action [15]. This package seeks to update current laws in alignment with the EU's 2030 climate objective while introducing fresh policy measures to facilitate the necessary transformative changes across the economy, society, and industry, ultimately achieving climate neutrality by 2050. This package aims to support this goal by reducing net emissions by a minimum of 55% (compared to 1990 levels) by 2030 [15]. The directive governing the cornerstone of European climate policy, namely, the EU ETS and the European Union, decided to reduce fossil fuels use and electricity consumption, both overall and at peak times, given the winter of 2022-23[9]. In June 2022, environment ministers within the EU reached a consensus on establishing the social climate fund. Subsequently, in December 2022, the European Parliament and the Council achieved a tentative political accord regarding the proposal. The Council adopted the new rules in April 2023 [14]. In this study, the geographical scope is Europe; hence, the Net Zero year will be as fit for 55 goals in 2050 in the reference case model (Scenarios with updated values in GET for CAP and carbon storage capacity, considering the recent literature).

3.2. Policies for Emission Reduction

3.2.1. EU ETS policies and possible future scenarios

Based on emission reduction policies and the target for reaching Net Zero emission to keep CO_2 ppm concentration in the atmosphere under 450, different measures and policies are implemented now as part of the EU ETS system [3]. As a general concept, there is a total CAP for GHG emissions, which means the total amount of emissions from different sectors is limited; based on this CAP, a limited allowance is allocated to various industries. In December 2022, a provisional agreement was reached to substantially tighten the emissions CAP of the EU ETS so that in 2040, the supply of allowances will be zero [3].

Limited allowance leads to a "carbon cost" due to scarcity of available allocation and higher demand. Furthermore, the energy-intensive industry sector will no longer receive free allowances, prompting changes in production processes to decrease their carbon footprint [7]. These reforms are expected to increase carbon costs on the emissions exchange by 2030. Following the revision, carbon costs have significantly increased, reaching over €100/tCO_2 for the first time in February 2023 [9]. Another essential parameter for addressing global warming and achieving the desired level of sustainability is setting the target year for achieving Net Zero emissions, which is 2050, in the latest EU ETS final revision [3]. The selection of a closer target year could make a pushing force towards different sectors to decrease their emission. Still, it should be realistic based on current limitations and technological development, considering society's welfare and problems like carbon leakage (Moving emitter industries outside borders with CAP and carbon cost policies) [3]. Another option for policymakers is" Phasing out old plants and technologies" such as nuclear plants due to their safety issues and coal power plants to decrease GHG emissions [3].

3.2.2. Future of Sustainable Electricity Production

In other research with a similar topic, a linear dynamic cost-optimization model named 'LIMES-EU' has been used to analyze the electricity sector and cover all emissions under the EU ETS mechanism [3]. The model analyzes comprehensive scenarios for the cost-efficient future development of the European electricity sector and the EU ETS. While the electricity sector is modeled in detail, emissions from the other sectors covered by the EU ETS include energy-intensive industry and district heating [3]. As a result, precise and meaningful relations have been revealed between CO_2 price, emission CAP, and emission from electricity, heating, and industries in a reference scenario (*Figure 2*) [3]. In the same study, for another scenario (Called reformed case), with tighter limits on emission and CAP, emissions from all sectors were reduced more rapidly, specifically in the electricity generation sector, compared to the reference scenario (*Figure 3*) [3]. In the reference case, CAP reached zero in 2055 while the CO_2 price reached 135 euro/tCO_2, and in the reformed case, CAP came to zero in 2040 with a carbon cost of 187 Euro/tCO_2 and reached 450 euro/tCO_2 in 2055.

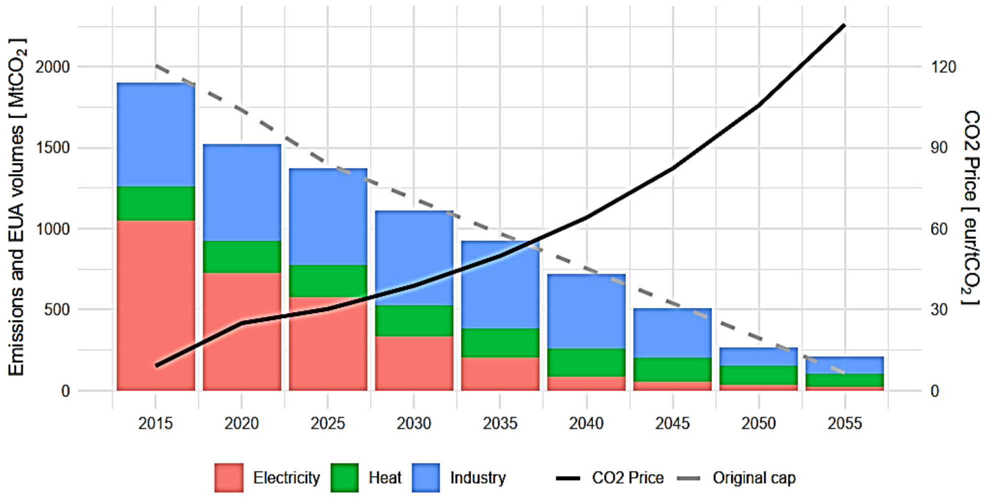

Figure 2. Emission CAP, CO_2 price, and emission (LIMES-EU reference case) [3]

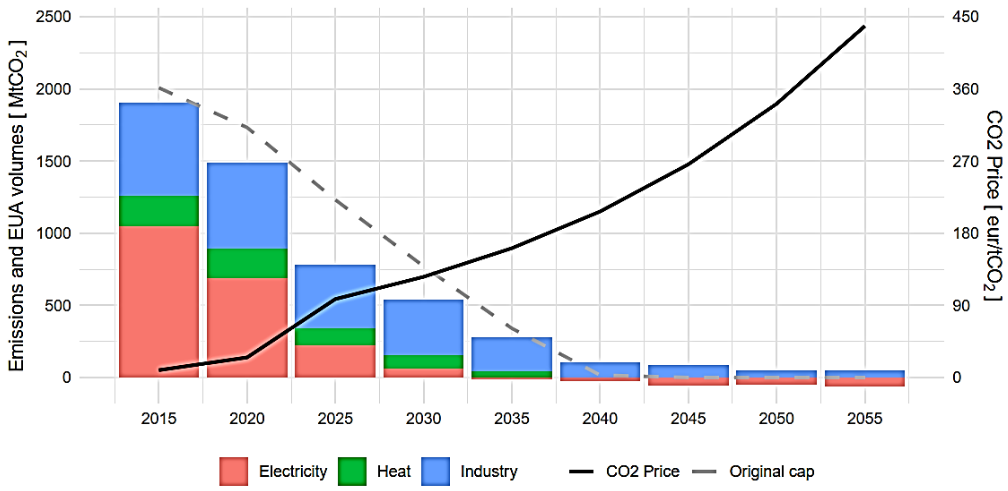

Figure 3. Cap, CO_2 price, and emission (LIMES-EU reformed case) [3]

3.2.3. Net Zero target year

Many countries have committed to reaching Net zero emissions in the coming decades. However, even if fully achieved, the current pledges are still far short of what is required to reduce global emissions of energy-related CO_2 to Net Zero by 2050 and to reduce global warming not to exceed 1.5 degrees Celsius [6]. To reach the Net Zero emissions target by 2050, the IEA has clarified a path that should be followed toward this goal. The following graphs (*Figure 4* to *Figure 6*) include projected data for Net Zero emissions by 2050 as a global energy sector roadmap [16]. *Figure 4* illustrates the suggested share of different technologies in the electricity market; up to 2050, renewables should produce a significant part of electricity while the share of nuclear would be unchanged, and there is a drastic decrease in the percentage of fossil fuels. The remaining share of electricity production by fossil fuels should be equipped with CCS (or utilization) systems. In *Figure 5* and *Figure 6,* CO_2 emission reduction by energy and technology has been illustrated, respectively, as IEA's suggestion for the future road map to Net Zero emission until 2050. To follow the suggested trends by IEA, the power sector (mainly electricity) should reach Zero emissions before 2040, while other technologies have more time until 2050 to get zero emissions. This clarifies the importance of focusing on the electricity sector towards the 2050 Net-zero target in research and papers, technological development, and policy-making progress.

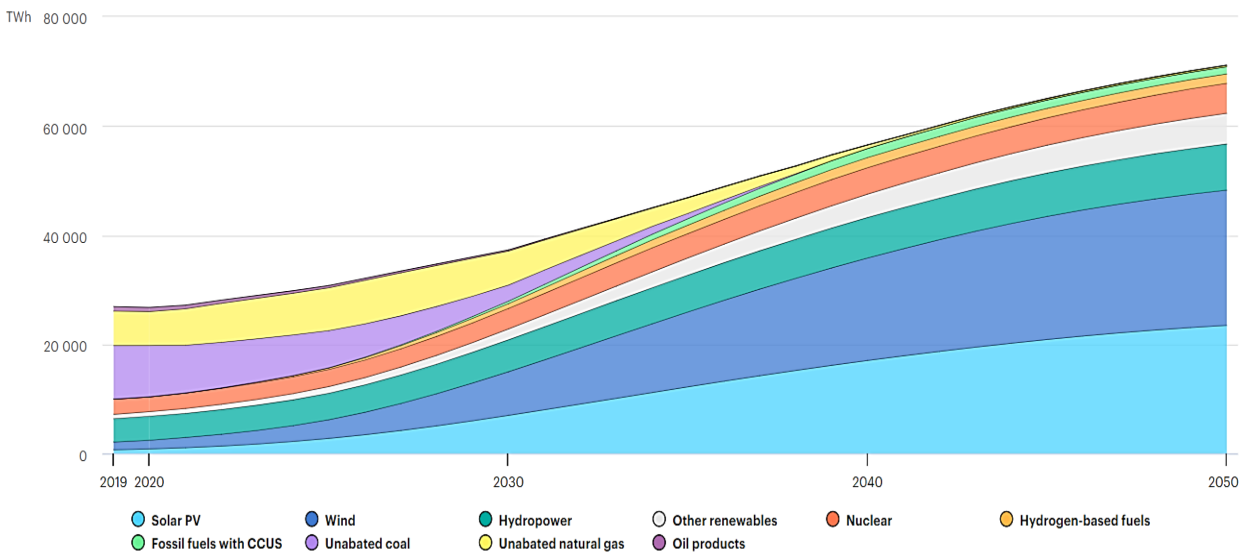

Figure 4. Global electricity generation by technology (IEA2021) [16]

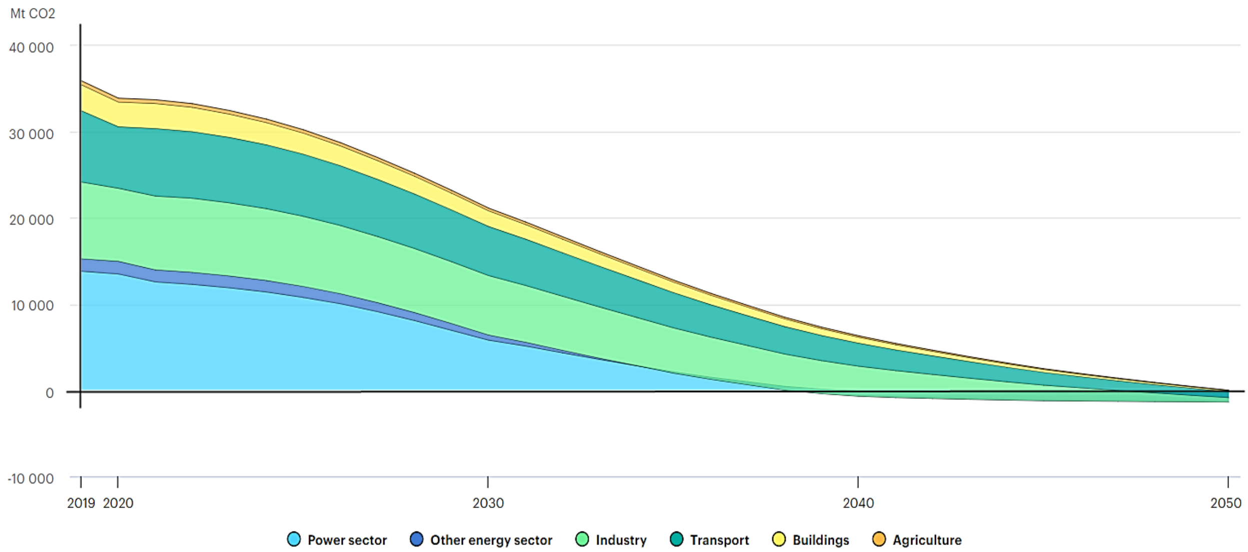

Figure 5. CO_2 emission by sector 2019-2050 (IEA2021) [16]

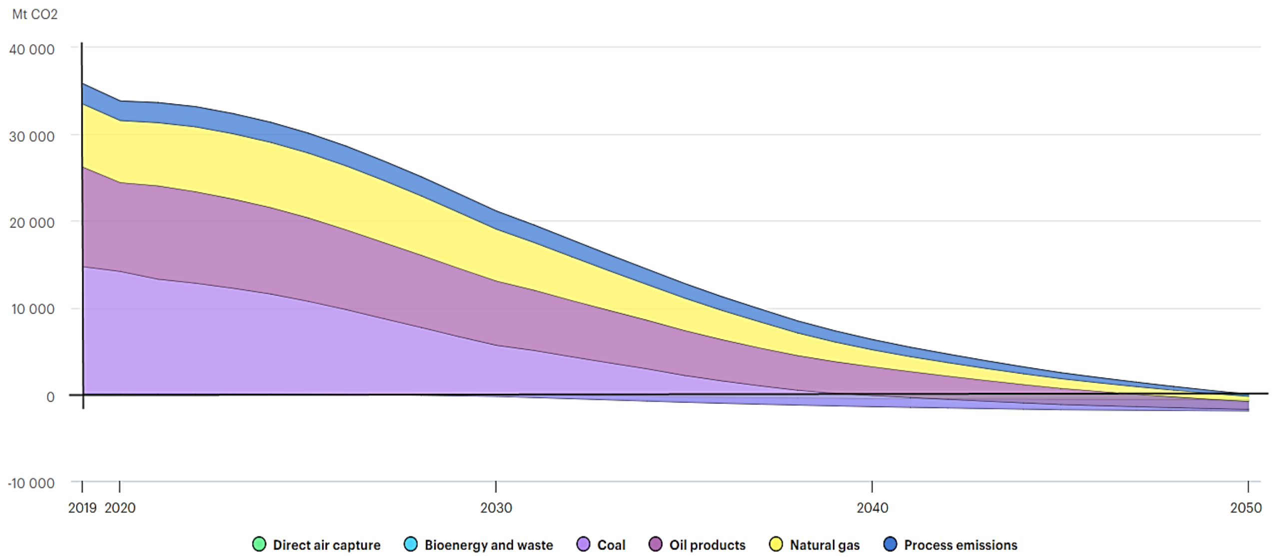

Figure 6. CO_2 emission by fuel 2019-2050 (IEA2021) [16]

3.2.4. Carbon Capture and Storage

When geological storage is available, CCS can reduce emissions from fossil-based energy and industry sources [17]. Using more CCS can make fossil fuels last longer by reducing their harmful effects, giving more opportunities for developing more sustainable technologies. Carbon capture and injection underground as a storage method is well-established in the oil industry aids in oil recovery, and enhances extraction from underground resources [17]. Unlike the oil and gas industry, there was not enough improvement in CCS for the power production sector, and this technology needs to be developed in electricity production. The estimated geological storage capacity is 1,000,000 $MtCO_2$, which is more than the requirements through 2100 to limit emissions and reach the target of not exceeding 1.5°C in the global warming process; however, available geological storage in each region could be yet a limiting factor for CCS for different industries [17]. Although CO_2 could be isolated permanently from the atmosphere by efficient selection and management of the available storage, implementing CCS in the power sector currently faces technological, economic, institutional, ecological, and social acceptance barriers. Current rates of CCS deployment are far below those in modeled and suggested pathways for reaching environmental targets and limiting global warming to 1.5°C [17].

3.3. Gas Turbine Power Generation

While combustion plants (heat, electricity, and mechanical drive) are the primary source of emissions under the EU ETS, in 2021, these installations accounted for 61% (814 Mt CO_2-eq) [2] of total verified emissions in the stationary part of the EU ETS [11]. Electricity and heat are crucial for initiatives to mitigate emissions and transition towards more sustainable energy systems.

Implementing sustainable measures in the electricity and heat generation sector is of utmost importance for the EU and the rest of the world. The leading technologies for electricity production include fossil combustion, nuclear, and renewables. Fossil conversion to electricity could be implemented by steam and gas turbines, while gas turbines will be considered in this study. Considering a more sustainable future for energy systems and electricity production, gas turbines could play two essential roles as a complementary technology for solar and wind electricity production. The first one is a need for compensating high solar and wind intermittency [18]; there is a need for flexible reserve capacity to maintain the stability of the grid. In other words, the ability of a fast-ramping natural gas power plant -using a gas turbine- can compensate for the variability introduced by wind turbines [18]. On the other hand, high electricity production during low consumption needs an extensive storage solution. At the same time, electrolysis could produce hydrogen at a low cost. Also, hydrogen can be made by electrolysis using low-cost renewable surplus electricity, stored, and converted back into electricity [19]. Gas turbine technology that can combust fuel gas, such as methane, could be used for electricity production from hydrogen. It could be applied on a large scale for converting stored hydrogen -or its mixture of 25% to 75% with NG – to electricity during the low wind and solar energy.

3.3.1. Definition of a Gas Turbine

A gas turbine is a turbomachine comprising three main components:

1. The compressor section is responsible for pressuring the inlet air.
2. The combustion chamber, where the fuel (gaseous or liquid) is combusted utilizing the compressed inlet air.
3. The turbine section, where the flow of hot gases from the combustion chamber converts to mechanical power.

These machines feature an outgoing shaft designed to power various loads. While the most prominent application is electrical power generation, they are also extensively used in industrial plants to drive compressors and pumps and in the transportation sector for large vehicles such as ships and planes. Gas turbines utilized in power plants constitute the most significant market segment. Although there is no single exclusive term to denote gas turbines specifically for power plants, they are occasionally called land-based gas turbines. *Figure 7* illustrates a simple gas turbine schematic with a connected shaft to a generator for electrical power generation. The generator could be connected to the gas turbine on the compressor or turbine side [21].

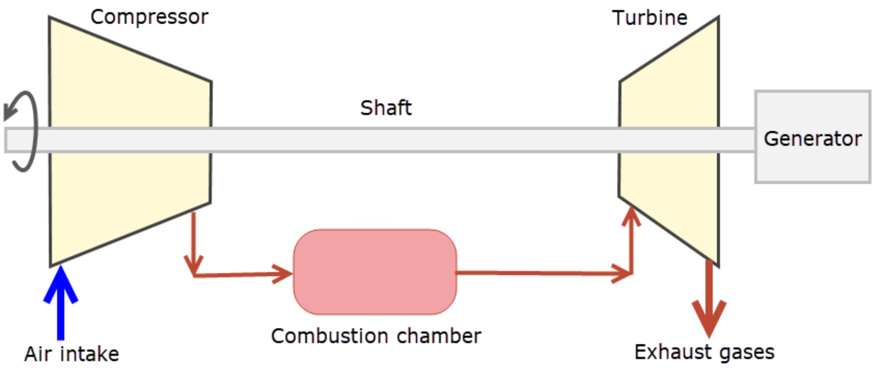

Figure 7. Gas Turbine parts and main components

3.3.2. Simple and Combined Cycle GT plants

A simple-cycle gas turbine follows a sequential path through three main components: a compressor, a combustion chamber, and a turbine. Finally, the flow will end up in the atmosphere from a part named the exhaust duct. In a combined-cycle system, the exhaust gas from a gas turbine with a high temperature generates steam in a heat recovery boiler with the technical name of Heat recovery steam generator (HRSG). After generating steam in the HRSG, the steam is routed to a steam turbine for further energy conversion and electricity generation [21]. In this study, a combination of simple and combined cycles is considered a possible solution for using a gas turbine for electricity production, which affects overall electricity production efficiency as described based on calculation in the next section. Also, heat and power production solutions will be considered where the exhaust gases will be used for heat generation. This combination would increase plant efficiency by converting fuel energy content to electricity and heat. The important fact in all three different types of plants is the application of a gas turbine as the main machine for converting fuels to another form of energy, such as electricity and heat, to address the demands in society.

3.3.3. GT Plant Efficiency and Load Factor

The electrical efficiency ($\eta_{el.}$) of the plant will be calculated based on the electrical output ($PowerEl_{out}$); for both simple and combined cycles (Equation 1), the same principle could be used for overall efficiency ($\eta_{overal.}$) for all different arrangements, including combined heat and power generation (CHP), as presented in Equation 2.

Equation 1. $\eta_{el.} = \frac{PowerEl_{out}(GT+ST)}{Q_{fuel}}$

Equation 2. $\eta_{overal.} = \frac{PowerEl_{out}+Heat_{out}}{Q_{fuel}}$

While:

$Heat_{out}$ *is total heat output of plant*
Q_{fuel} *is plant input energy, fuel energy content*

This study focuses on the electricity production sector, and energy conversion from fuel to electricity (not heat) will be considered in the power plants analysis, and electrical efficiency is used for all calculations and modeling purposes. On the other hand, there is another critical factor in calculations: a machine could work 365 days per year and 24 hours per day, which could be unrealistic due to the regular inspection and maintenance plans or unplanned outages. The "Load factor" (LF) is calculated to determine how much in percent the machine is under operation during a year. The load factor could be calculated by dividing actual plants' working hours by 8760 hours.

Equation 3. $$LF = \frac{Actual\ working\ hours\ for\ machine}{8760}$$

3.3.4. Gas Turbine Emission

While most CO_2 emissions from power generation sectors are related to hard coal and lignite, accounting for 63% of all emissions from combustion installations, natural gas-powered plants – using gas turbines- contribute 17% of emissions from such facilities [11]; this fact could illustrate an opportunity for future of power generation by gas turbines as a more sustainable alternative for other fossil fuels (coal) with high emissions. In the next step, decreasing emissions from gas turbines should be considered. During the construction of robust models and analysis of future scenarios for the EU ETS, it is vital to consider the energy market and the role of gas turbines, along with sustainable solutions for them to decrease emissions. At the same time, they could have a complementary role in sustainable energy systems, as mentioned before, with intermittency compensation (with a fast ramp-up feature) and storage solutions (burning hydrogen as a RES storage solution). Gas turbine sustainable solutions can potentially decrease emissions to foster the development of a low-carbon energy system. Various approaches can be taken to reduce GHG emissions from gas turbines. One method involves enhancing the efficiency of gas turbines, thereby reducing fuel consumption and subsequent CO_2 emissions. Increasing efficiency in gas turbines could be implemented by improving individual parts and machine integrity; it is also possible to use heat recovery systems for high-temperature exhaust gases to produce heat or electricity using steam turbines. Another approach entails transitioning to alternative fuels, such as hydrogen or biofuels, which generally emit less or zero GHG emissions compared to fossil fuels. However, this transition necessitates substantial investments in new infrastructure, and the availability of these fuels currently needs to be improved. Additionally, the significance of CCS technologies in curbing gas turbine emissions is underscored in reports from the EEA. Although CCS is a relatively new solution, it holds promise for addressing this issue [22]. In this study, both possibilities for using hydrogen fuel and carbon capture (and storage or use in other places) will be considered as technical sustainable solutions for future power generation using gas turbines as an effect of EU ETS policies.

3.3.5. Gas turbines in a sustainable future

As mentioned in the EU ETS introduction section, continuing current policies in the EU, and expected projection of trends over the next decades will lead to less allowance by decreasing the emission CAP and high emission prices, resulting in less emissions from fossil fuels. In this context, investors and producers may prioritize investing in removing fuels with high emissions, such as oil, diesel, coal, and lignite. However, gas turbine electricity production could maintain importance due to two significant advantages over fossil primaries. The relatively low investment cost of gas turbines with rapid operational features -essential to shave demand peaks- in addition to lower emissions compared to coal and lignite units, by burning natural gas "NG" make them a viable option for developing decentralized production in the future. On the other hand, GT could burn new carbon-free fuels such as hydrogen, biofuels, and electro-fuels, making this technology more competitive with other traditional ones (specifically coal power plants) and maybe a complementary technology for energy storage in future sustainable energy generation [23]. By having more sustainable renewable energy share such as solar and wind, the possibility and importance of energy storage is increasing. Hydrogen is an appropriate option for storing extra electricity production from wind, and solar and gas turbines could convert stored hydrogen back to electricity during peak times [19].

3.3.6. Current Share of Gas Turbines in Electricity Market

In this study, electricity production from natural gas will be considered an application of gas turbines in power plants. To evaluate the current and history of power generation by gas turbines, it is possible to consider electricity production from natural gas. *Figure 8* (data from the IEA report) demonstrates electricity production by different European sources (GWh) from 1990 to 2020. Natural gas-based electricity production increased until 2010, and after a short-term decline, production started to increase again in 2015. As a short review of the data and statistics from history (*Figure 8*) with the assumption of continuing the same trends, it is possible to predict a considerable decrease in power generation from coal and oil, which should be compensated by wind, solar, and NG. Analysis of historical trends presented in this section reveals expanding electricity production from renewables or NG, highlighting the role of the gas turbine in the future technology mix.

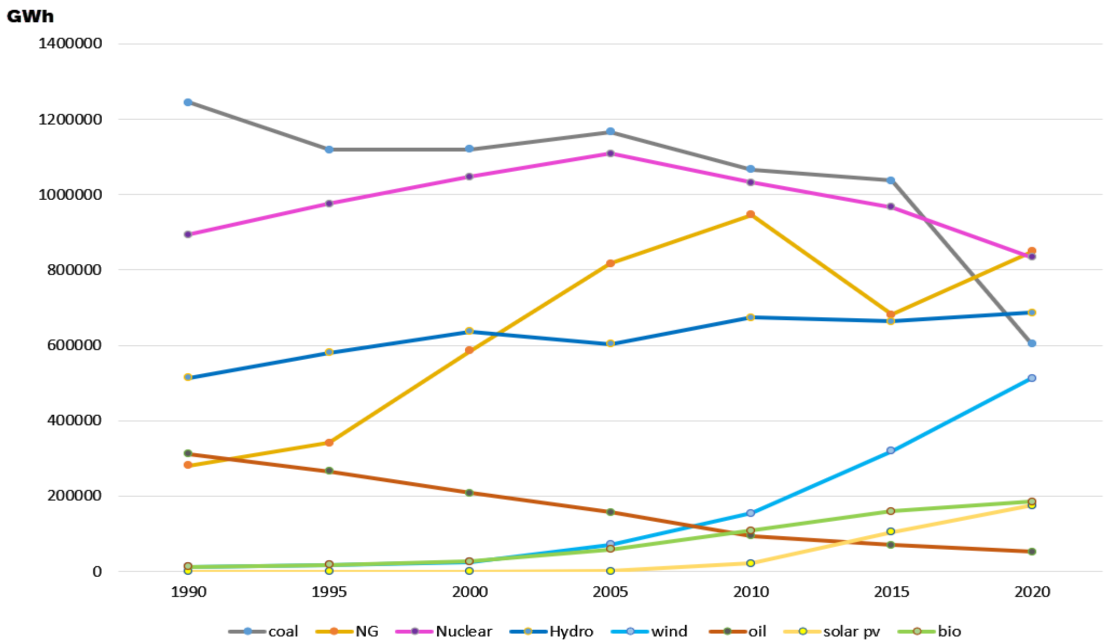

Figure 8. Electricity generation by source in Europe 1990-2020 in GWh [24]

In 2022, the EU produced 2 641 TWh (Terawatt-hours) or 9,5 Exajoule (EJ) of electricity. Almost 40% came from renewable sources; fossil fuels comprised 38.6%, and nuclear electricity was over 20%. Gas was the primary fossil fuel used to generate electricity (19.6%), followed by coal (15.8%) [20]. *Table 1* demonstrates various primary energy sources in Europe for power production, while 517,6 TWh (19,6%) of electricity is produced by natural gas. This number could be compared with future natural gas and hydrogen to electricity [20]. A switch from coal to gas electricity production is a significant factor that propels the European gas turbine market. In 2016, around 8 GW of coal plants were closed in Europe. Also, Europe has announced the closure of an additional 7 GWs of coal power plants during 2017-2020, representing less than 5% of the total coal fleet in the region. The share of gas-fired power generation in Europe grew from 15.5% in 2015 to 20.8% in 2018 [25].

Table 1. Share of primary sources in electricity production in the EU for 2022 [20]

Primary energy source	**Renewables 39.4%**				**Nuclear 21.9%**	**Fossil fuels 38.7%**			
	Wind	Hydro	Solar	Biomass		*Gas*	Coal	Oil	other
Share%	15.9%	11.3%	7.6%	4.6%	21.9%	*19.6%*	15.8%	1.6%	1.7%
TWh	419.9	298.4	200.7	121.5	578.4	*517.6*	417.3	42.3	44.9
EJ	1.5	1.1	0.7	0.4	2.1	*1.9*	1.5	0.15	0.16

SGT-800 power production capacity is 62MW.

4. Methodology

This section describes the methods and tools in this study, the modeling process, and the analysis of the results. In addition, the data sets and inputs needed for modeling, theoretical and technical limitations, boundaries, and assumptions will be discussed. To model future scenarios for the EU ETS, simulations of the future energy system with two significant targets of “Cost Optimization” and “Reaching Net Zero emission” will be implemented. The method for modeling in this study is through a script in the GAMS software (General Algebraic Modeling System), a high-level modeling software used to model complex systems in economics, engineering, and other fields. The script forms an optimized energy systems model named the Global Energy Transition (GET). Azar and Lindgren initially devised the GET model [33], and after, it has been expanded upon in studies by Grahn, Hedenus, Lehtveer, and their respective collaborators [34],[35],[27]. It is a "bottom-up" systems-engineering model of the global energy system. This model adopts a linear programming approach, with time steps of 10 years, to minimize costs while addressing carbon mitigation strategies. Its primary goal is to minimize the discounted total energy system cost over a specified period (typically 2000-2100) while simultaneously fulfilling defined energy demand and carbon limitations. For this study, adjustments were made to incorporate potential carbon costs across various sectors within the EU ETS framework. Furthermore, modifications were implemented to check the Net Zero years and set up a cumulative emission CAP throughout the study period, leading to the Net Zero target.
Process-wise, modeling and analysis in this study involve several steps, including the following:

1. Data Collection and Preparation: In this step, relevant data have been collected and prepared in the GAMS script. This data includes information on energy market factors, such as fuel prices (valid for coal, oil, NG, and uranium), investment costs for different energy conversion technologies, and available energy resources. In addition, data related to the EU ETS policies, such as emission CAPs, carbon cost, and NetZero target year. Investment and operating costs for gas turbines will be used in the modeling as input data for converting fuel gas and hydrogen to electricity.

2. Model Development: The GAMS script and modeling code used for this study have been developed and changed in a few sections on equations for annual costs calculation and carbon costs inclusion in the script, as well as some input data sets, to incorporate the relevant data and generate scenarios as the future of the EU ETS. The model includes assumptions about the impact of energy market factors on the application of gas turbines, as well as the effectiveness of sustainable solutions for reducing emissions, specifically hydrogen as a carbon-free fuel (and storage media for RES) and carbon capture system in case of natural gas combustion in GTs. Furthermore, some changes are implemented to the

code to consider the Net Zero target year globally and in Europe region base. Also, modifications to have the possibility of technologies phase out for electricity production based on nuclear (uranium) and coal.

3. Model Execution: The GAMS script was executed to generate scenarios for the future of the EU ETS based on the input data and modeling code. The results would calculate future demand and generation, including different technologies and sectors.

4. Results Analysis: Based on the output generated by the GAMS script, results will be discussed and interpreted to find the most effective strategies for reducing emissions associated with gas turbine usage in the future. The implications of these findings for the energy market and policymaking will be discussed. For a better understanding of outputs and their effects on gas turbine future in the electricity market, key parameters will be considered for evaluation of future image from the electricity market, technology mix, and important items that figure out the role of the gas turbine in the electricity production sector in Europe.

4.1. Theoretical Limits

There are several potential limits for studying and modeling future energy transition, considering various technical parameters, market conditions, and different policies such -as EU ETS- as constraints in addition to political and social factors. Firstly, it is essential to acknowledge that modeling the future is inherently uncertain, and any projections are subject to a range of unknown variables and unpredictable events and are very dependent on assumptions and restrictions made in input data to the model. Therefore, while modeling can provide valuable insights for decision-making, the findings should not be considered predictions. However, the modeling in this study is based on calculations for the least cost solution to reach environmental goals and emission reduction targets, and results are not based on predictions.

In addition, many uncertainties in the future could affect the real upcoming scenarios. Also, some unplanned events or unknown variables could impact the results in the future, and it is only possible to consider some of them during the modeling process. For example, Ukraine's 2022 invasion changed the energy market drastically and created new scenarios worldwide. Also, unexpected global climate changes could impact solar, wind, and hydro energy resources and potential changes in energy demand for indoor heating and cooling. Another challenge in this study is the "complexity of the energy market," which involves various interrelated factors such as technological advancements, economic conditions, market characteristics, changing regulations, and potential behavior aspects of people and societies. This complexity makes it challenging to isolate the impact of individual variables on the future of the EU ETS and gas turbine application in the electricity market. Furthermore, there may be limits to the availability and quality of data on different input variables, which could impact the accuracy of the modeling calculations and outputs. Additionally, political, and social factors may influence the trajectory of the EU ETS and the adoption of sustainable gas turbine emissions reduction technologies. Changes in government policies, public opinion, and future international agreements could significantly impact the energy market and the viability of different modeling scenarios. Finally, a cumulative global emission CAP has been applied as a climate policy during the modeling process. This cumulative emission CAP is a global limit and should be followed by all regions and all countries as a worldwide attempt to reach the Net Zero emission target. Therefore, this assumption could be a limit in the study since it is not just a decision and acts under the control of the EU ETS domain and European policymakers as the main geographical domain in this study.

4.2. Linear Optimization with GAMS

GAMS, as a high-level modeling language, is used in this study for simulating and modeling future energy systems through linear optimization techniques. This intuitive and flexible language allows the formulation of complex optimization problems efficiently and enables models to be developed and run on various operating systems and hardware architectures. The advantages of using GAMS include switching between different solvers without altering the model formulation. GAMS was the first software system to combine mathematical algebra with conventional computer programming concepts to solve optimization problems effectively [27]. By utilizing GAMS linear modeling codes, it would be possible to create various scenarios using a range of input data for analyzing and modeling future scenarios of EU ETS, along with other vital input parameters. This modeling and analysis can provide policymakers and stakeholders with a better understanding of the potential effects of different measures and technological advancements on the energy market and the future of EU ETS. Additionally, this modeling can assist in identifying strategies to promote sustainable solutions and reduce emissions from gas turbines. By using GAMS, a global energy transition model, "GET," was developed to provide a tool for decision-makers towards a better understanding to reach energy demands worldwide [27], considering available energy supplies globally, with optimum costs and increased sustainability.

4.3. GET, an Energy Transition Model

The GET model has been developed and extended to address research questions related to the sustainable development of the global energy system. GET is a cost-minimizing "bottom-up" systems engineering modeling script for global energy calculations using GAMS as a linear programming software. The model was developed to investigate emission reduction strategies considering minimizing total energy system cost while meeting a specific energy demand and a carbon constraint [28]. The model focuses on the energy supply side and various end-use sectors consisting of electricity, transport, feedstock, and heat demand in residential, commercial, and industrial processes, while different energy sources and technologies are available in each sector to meet the applications [28]. Technologies are specified by the energy carriers, which they can potentially convert, and those are parameterized using, e.g., investment and fuel costs, efficiencies, capacity factors, and emissions. Calculations for demand in the future are based on the MESSAGE B2 scenarios, considering the expansion of the world population, having an intermediate level for economic development, and an environmental target for a stabilization level of 450 ppm CO_2 by 2100 [16]. Prices and costs are represented in absolute terms without considering future inflation. Net present value calculations utilize a global discount rate of 5% annually.

The model operates with perfect foresight, enabling it to identify the least-cost solution for the entire study period. Consequently, limited resources such as oil and bioenergy are allocated within the model to the sectors where they can be used most cost-efficiently when meeting ambitious CO2 reduction target. The model assumes that all technologies are universally available across regions, as global technology dissemination is not considered a limiting factor. The model divides the world into ten regions, aggregating regional solutions to provide global results [28].

GET-11 - the version used in this study- structured to have flowing energy resources between the regions (excluding electricity) with movement costs. The model aggregates regional solutions to provide global results and controls CO_2 emissions with annual maximum upper limits towards stabilizing atmospheric CO_2 concentration, while other GHGs are not considered. The applicable period for the model is designed for the 1990-2140 period, with 10-year time steps. For this study, the period from 2030 to 2100 has been considered. It is essential to note that this cost-minimizing energy system model does not predict or forecast the energy system's future development. Instead, it serves as a tool to comprehend the system's behavior and connections among various energy technology options in different sectors by optimization of resource distribution and usage, with some cost and environmental constraints [28].

4.3.1 Data Sets and Inputs

During this study, for modeling the future energy transition, four groups of data sets and inputs have been used:

1. Data sets from the GET model default inputs. The GET model uses different types of input data, provided, and developed by Chalmers University of Technology [27], and includes the following items (but are not limited to them):

- Energy conversion technologies convert different kinds of energy sources or carriers to each other (if possible), including gas, oil, coal, hydrogen, wind, bio, solar, uranium, electricity, etc.
- Different transport modes and heating modes
- Fuel consumption in different sectors, considering the demand growth in the future.
- Conversion efficiencies, load factors, and investment costs
- Population in the world and its increase over the following years.
- Fuels price for different fuels (coal, oil, gas, bio, uranium, …)
- Energy resources availability in different regions

2. Input data for the SGT-800 gas turbine (Calculated outputs from Thermo-flow power generation modeling software, version 30.0 [30]). The gas turbine plant's investment cost (CAPEX) and electricity efficiency for gas turbine power plants, as main outputs from the Thermo-flow modeling process, are used as newly updated inputs for the GET model. These parameters are the results of simulating simple and combined cycle arrangements for gas turbine plants with NG and hydrogen fuels and are presented in *Table 2*.

3. Endogenously produced data sets include internally calculated values based on the given initial values in group 1. These data sets are produced by internal GET calculations using different equations during the modeling process. Important items in this group are related to future values of some parameters such as fuel price, population, available energy resources, energy demand in a different sector, and energy import and export related to each region. The main difference between this data set and Group 1 is that Group 3 values are results from internal model calculations; in contrast, data in Group 1 are exogenously given inputs as initial values for the model.

4. Newly updated data based on the literature: This group consists of the maximum allowed cumulative emission CAP to reach the Net Zero emission target (and desired temperature increase goal of 1.5 degrees centigrade), with a maximum of 500,000 $MtCO_2$ until 2100. Based on the latest IPCC report, this data group contains the maximum available geological CO2 storage capacity, 1,000,000 MtCO2 [17].

In this study, the SGT-800 gas turbine model from Siemens Energy AB, a middle-range gas turbine product, has been considered the default gas Turbine machine for electrical power generation plants.

This single-shaft turbine consists of a two-bearing rotor, a 15-stage compressor, and a three-stage turbine. The output power range is 45-62 MW with a gross efficiency of 38.4% to 41.1% in simple cycle mode [26], while in this study, the latest design of this model with 60 MW has been considered.

Table 2. Gas Turbine data from Thermo-flow modeling software - (SGT-800)

Plant configuration and fuel type	CAPEX (USD/KW)	Electrical efficiency
Simple cycle (SC) with NG	878.9	40.9%
Simple cycle (SC) with H2	878.9	41.1%
Combined cycle (CCPP) with NG	1080	57.7%
Combined cycle (CCPP) with H2	1128	57.2%

4.3.2. Outputs

GET results are extensive in the range of type of parameters, consisting of different output data sets, which have been managed into the Excel sheets as model results. The most related and valuable data are extracted as curves and trends from 2030 to 2100 for better understanding, comparison, and analysis. Modeling output parameters could be divided into two groups, and the first group will be used directly for analyzing, comparing, and making conclusions in this study; these parameters are related to gas turbine applications, including electricity production by NG and hydrogen in addition to electricity production using CCS for NG fueled GTs. This output group has been demonstrated for future scenarios in the results and analysis chapter (*Table 3*). The important point regarding the output cumulative values is summarizing the output values between 2030 and 2100, with an interval of ten years (see section 4.10). Therefore, the cumulative for each item results from summing up values for years 2030, 2040, ...,2090, and 2100 for analysis and comparing purposes. The second output group consists of data and trends, which could be interesting as additional data for readers and valuable for other researchers as their input data (*Table 4*). This group of outcomes is not used directly for analyzing the results and can be found in the appendices.

Table 3. The main outputs for analyzing the modeling results.

Output parameter	Unit	Description
Electricity from NG (Annual trend)	EJ	Electricity production trend by natural gas combustion (GT) between 2030 and 2100, with ten-year intervals.
Electricity from NG (Cumulative values)	EJ	Cumulative electricity production by natural gas combustion (GT) for the 2030 to 2100. (For model output years, not all years)
Electricity from hydrogen (Annual trend)	EJ	Electricity production trend by H2 combustion (GT) between 2030 and 2100, with ten-year intervals.
Electricity from hydrogen (Cumulative values)	EJ	Cumulative electricity production by H2 combustion for the 2030 to 2100. (For model output years, not all years)
Electricity from NG + CCS (Annual trend)	EJ	Electricity production trend by natural gas combustion (GT) and carbon capture technology between 2030 and 2100, with ten-year intervals.
Electricity from NG +CCS (Cumulative values)	EJ	Cumulative electricity production by natural gas combustion (GT) and carbon capture technology for the 2030 to 2100. (For model output years, not all years)
Electricity from RES, wind, and solar (Cumulative values)	EJ	Cumulative electricity production by wind and solar sources for 2030 to 2100. (For model output years, not all years)
Electricity from fossil, carbon-intensive sources, coal, and oil (Cumulative values)	EJ	Cumulative electricity production by carbon-intensive fossil fuels, including coal and oil sources, for the 2030 to 2100. (For model output years, not all years)

Table 4. Additional output data from the modeling

Output parameter	Unit	Description
CO_2 concentration in the atmosphere (ppm)	ppm	This parameter is the final goal of all energy and emission policies to reach the target 1.5-degree Temperature increase by 2100.
Emissions from all sectors	$MtCO_2$	Amount of CO_2 emission for all sectors in Europe.
Emission for electricity sectors	$MtCO_2$	Amount of CO_2 emission for electricity production sectors in Europe.
Total energy supply (EJ)	EJ	Total energy supply mix for all sectors (global/Europe)
Electricity production technology mix (EJ)	EJ	Electricity production technology (resource) mix trends (global/Europe)
Hydrogen production (EJ)	EJ	Hydrogen production trends by different sources (global/Europe)
CO_2 captured	$MtCO_2$	Captured CO_2 for different sectors in Europe
CO_2 storage	$MtCO_2$	Stored CO_2 in Europe

4.4. Modeling Assumptions

Modeling and study assumptions could be categorized into three main groups: energy market and economics, policies, and technical parameters.

4.4.1. Energy Market and Economic Assumptions

- Fuel prices: These are based on the GET model default values as start prices (USD per GJ of energy content in fuels) and will be determined endogenously during the modeling progress each time based on fuel availability, cost optimization, and scarcity factors.
- Investment costs: based on GET defaults for energy conversion technologies and method (USD/KW) but updated for NG and hydrogen to electricity regarding the plant modeling by thermo-flow and for simple and combined cycles plants using the SGT-800 GT model.
- Time horizon: It is between 2030 and 2100 and will be fixed during the modeling.
- Future interest rate: discount rate of 5% constant during the modeling for all cases.
- Regarding the energy flow between different regions, import and export are considered between the ten regions in the model.

4.4.2. Policy Assumption

These assumptions are related to EU ETS measures and policies:

- Net Zero emission, target year: it is considered as 2050 for the EU and 2100 for the other regions in the world for the reference (base) case.
- Emission total cumulative CAP: The cumulative CAP is a global limit that is not under the control of EU ETS; in this study, it is assumed that all other regions in the world will follow this limit besides EU ETS.
- Carbon cost: assumption for future different values of carbon cost as modeling input for some scenarios. Carbon costs of 0, 100, 200, and 500 USD/t CO_2 have been considered, and they remain fixed during the modeling progress in each scenario (cases).

Complementary Policies

- Supporting policies for RES and hydrogen technologies: It is assumed that changing the technology investment cost will affect the penetration of the technology in the electricity market. With changing CAPEX in some cases, different renewables (solar and wind) penetration will be examined in the model. It assumed that supporting policies would decrease CAPEX for RES and hydrogen.
- Phasing out old technologies: As possible scenarios, phasing out nuclear and coal power generation will be considered until 2050 by more limitations from the

policymakers. This is a technological parameter, but policies could significantly affect implementation [3].

4.4.3. Technical Assumptions

- The load factor for all electricity production plants is 95%
- For gas turbine power plant efficiency calculations, NG and hydrogen are considered as fuels.
- Plant for GT efficiency and CAPEX calculation by thermos-flow located in Germany.
- Efficiencies for other energy conversions are based on the default values in the GET model.
- Efficiency of all energy conversion technologies is constant during the modeling progress.
- CCS technology is considered a possible solution in the model.
- Availability of different energy sources such as fossil fuels, uranium, wind, solar, and hydro are used from the GET default values, although for having more accurate calculation in the model outputs, up-to-date values for available solar and wind energy have been updated based on the latest available data from global solar and wind atlas [29].

4.5. Study Boundaries

This study's period for modeling is from 2030 to 2100, while the geographical boundary is defined as the European Union. Although all ten regions worldwide are active for modeling purposes, the focus is only on Europe. For power generation in Thermoflow software, Germany has been selected as the country for gas turbine plant installation, and plant simulation outputs are expanded to all EU as inputs to the GET model. As the central concept and structural assumptions in our modeling, the description of the energy system in the model is a simplification of reality and is limited in four important respects:

(i) Considers a limited number of technologies,
(ii) Assumes price inelastic demand,
(iii) Makes selections based on cost-effectiveness,
(iv) Has perfect foresight (fixed interest rate) without the uncertainty of future costs, climate targets, or energy demand [27].

4.6. Modeling Limits

In this section, some notable limitations for modeling are described:

Scope limits

As a scope limit in Linear models, calculations are often simplistic and may not follow the full complexity of the real world. Using GAMS linear modeling codes to estimate the future of the EU ETS and the energy market may result in simplified or unrealistic scenarios due to limitations in capturing the complexity of these systems. In addition, Linear models rely on certain assumptions about market behavior and the relationships between variables. Incorrect assumptions or data limitations could lead to inaccurate results.

Flexibility limits

Furthermore, the GAMS linear modeling code may not be flexible enough to incorporate changes in policy or other external factors that could impact the future scenarios of the EU ETS and the energy market. The model's inability to adapt to changing circumstances could limit its accuracy in calculation and anticipation of future outcomes.

Time horizon limitations

Linear models are often unsuitable for long-term forecasting because they need to consider changes in technology, policy, or external factors that may emerge over time. GAMS linear modeling codes may be limited in their ability to accurately predict longer-term scenarios for the EU ETS and the energy market since the time scale in the GET modeling script is ten years.

Model validation

For the model results to be accurate and reliable, it is vital to consider the quality of the input data and assumptions. It is crucial to validate the model thoroughly.

In conclusion, while linear modeling tools such as GET can help to model future scenarios for the EU ETS and the energy market, it is essential to understand and consider the potential limitations of these models carefully. Sensitivity analyses are essential when analyzing the results. Tests are carried out to understand better if results are robust or sensitive to changes in input data.

4.7. Thermoflow, Power Plant Modeling Tool

Thermoflow is an advanced modeling System that uses an updated database based on the official real-world information. This software's main application is optimizing design for new power plants, ensuring that design could meet both technical and economic requirements for each design situation. Outputs could be useful for designers and investors, and they are helpful for better control over the decision-making process, enabling assessing options impartially and avoiding being influenced by generic solutions that may not be the most suitable for the specific application. The outputs consist of power plant configurations and technical parameters aligning with the design criteria. This modeling tool functions exclusively for gas turbine-based plants, with the possibility of simulating various power generation configurations and scenarios [30]. In this study, simulations using this modeling tool have been carried out for simple and combined-cycle plants, considering natural gas and hydrogen as gas turbine fuel. The most important outputs from this modeling tool for this study are power plant electrical efficiency (the efficiency of converting energy to electricity, see *Equation 1*) and plant CAPEX (Capital Expenditure per KW of plant capacity). Thermoflow modeling outputs serve as the input data for the GET model. For this study, Thermoflow version 30 has been used.

4.8. Modeling Scenarios

As the central part of this study, modeling for future energy transition will be implemented based on the numerous potential scenarios (Cases) represented by EU ETS measures and different electricity technology mixes, including gas turbine power generation. Two main input categories in the modeling process are "technological parameters" related to electricity production (using gas turbines) and different possible "policies for emission reduction" under EU ETS. To address each Scenario with unique technical and policy configuration, each case has been labeled by a specific code, listed in *Table 5*, and more descriptions for each Scenario are mentioned in the following sections: 4.8.1 to 4.8.9. The main parameters, changed as input variables, to create each specific scenario are listed as follows:

- Net zero target year
- Cumulative emission CAP
- CO_2 prices
- Efficiency of electricity production (SCPP or CCPP configurations, acronyms explained below)
- Available CO_2 storage capacity
- RS and hydrogen technologies penetration in electricity production (different CAPEX)
- Fossil fuel different (more expensive) cost (NG, oil, coal)
- Phasing out nuclear and coal electricity production plants until 2050

In the coding system, SC, and CC present simple and combined cycle power plants (also different efficiencies), while A, B, and C in the second position are related to different Net zero target years.

Table 5. Specific codes for different scenarios and their definitions (for simple cycle-SC).

In this table, "m" stands for million after some numbers and def. It stands for default values (in GET inputs).

Scenario Code	Case description	Net Zero Year	Emission CAP	Carbon Cost	El. Eff.	Storage capacity	RES CAPEX	H2 CAPEX	Fuel price
			Mt CO_2	USD/t CO_2		Mt CO_2	USD/KW	USD/KW	USD/GJ
SC-A	GET model default values	Gl. 2100	700,000	0		2m			
SC-A3 Ref.	CAP=500,000 & CS=1m			0		1m			
SC-A3-1	C-cost 100 (El. & industry)			100		1m	GET defaults		
SC-A3-2	C-cost 100 (All sectors)			100		1m			
SC-A3-3	C-cost 200 (El. & industry)			200		1m			
SC-A3-4	C-cost 200 (All sectors)			200	36-41%	1m			
SC-A3-5	Expensive oil/coal fossil fuel			0		1m			
SC-A3-6	Expensive Fossil fuels + C-cost 200 (all sect)			200		1m	GET defaults		oilx2, coalx1,5
SC-A3-7	Nuclear Phase-out in 2050			0		1m	GET defaults		
SC-A3-8	Coal Phase-out in 2050		500,000	0		1m			
SC-A3-11	A3 and Carbon storage =0			0	36-41%	0	GET defaults		
SC-A3-12	A3 and Carbon storage =5m	Gl. 2100 EU2050		0	36-41%	5m			
SC-A3-21	A3 and more RES share						0,5x CAPEX	GET	GET
SC-A3-22	A3 and more H2 share			0	36-41%	1m	GET	0,5x CAPEX	GET
SC-A3-23	A3 and more RES and H2						0,5x CAPEX	0,5x CAPEX	GET
SC-A3-24	A3 and less RES share						1,5x CAPEX	GET	GET
SC-A3-90	A3 and smaller CAP 250Gt		250,000	0					
SC-A3-91	A3 + CAP 250 + C-cost 200			200					
SC-A4	Larger CAP compared to A3			0			GET defaults		
SC-A4-1	A4 + C-cost 100 (all sect.)			100	36-41%	1m			
SC-A4-2	A4 + C-cost 200		1,7m	200					
SC-A4-3	A4 + C-cost 500			500					
SC-A4-4	A4 + C-cost 200+ exp. Fuel			200			GET	GET	oilx2, coalx1,5
SC-B	A3 + Global Net Zero 2050			0			GET def.	GET def.	GET def.
SC-B2-1	B + more RES penetration	Global 2050		0			0,5x CAPEX	GET	GET
SC-B2-3	B + more RES&H2 penetration		500,000	0	36-41%	1m	0,5x CAPEX	0,5x CAPEX	GET
SC-B3-4	B + C-cost 200 (all sectors)			200			GET	GET	GET
SC-C	A3 + Global Net Zero 2100	Gl. 2100	500,000	0	36-41%	1m	GET def.	GET def.	GET def.

4.8.1. GET default inputs

As our first run, the GET model with all default input values and parameters was run to check the results, while later, some key parameters and constraints were updated based on the latest available data from the literature or GT plant simulations in Thermoflow to see the possible scenarios and following consequences (Case A, *Table 6*).

Table 6. Scenario with GET model default input values.

Case	Case description	Emission Net Zero year	C-cost	RES CAPEX	H2 CAPEX	Fossil fuel price
	GET default case:		USD/tCO₂	USD/KW	USD/KW	USD/GJ
SC-A Or CC-A	Simple cycle gas turbine plant Cumulative emission CAP: 700,000 $MtCO_2$ CO_2 storage capacity: 2,000,000 $MtCO_2$	Global:2100	GET Default =0	GET Default	GET default	GET default

4.8.2. Reference Case

In this scenario, as the study reference scenario, CO_2 storage capacity has been updated based on the latest IPCC report [17]; it was 2,000,000 as the default GET model, but in the reference case and all other cases (except scenarios with different CO_2 storage capacity values), 1,000,000. $MtCO_2$ has been mentioned in the latest IPCC report [17]. Furthermore, the value of allowed cumulative emission until Net Zero years has been updated to 500,000 Gt CO_2 in the reference case based on the same IPCC version, and Europe's Net Zero emission target year changed to 2050, while it is 2100 for all other regions worldwide (Case A3, *Table 7*).

Table 7. Reference scenario, GET model with updated inputs.

Case	Case description	Emission Net Zero year	C-cost	RES CAPEX	H2 CAPEX	Fossil fuel price
	Reference case:		USD/tCO_2	USD/KW	USD/KW	USD/GJ
SC-A3 Or CC-A3	Simple cycle gas turbine plant Cumulative emission CAP: 500,000 $MtCO_2$ CO_2 storage capacity: 1,000,000 $MtCO_2$	Global:2100 EU:2050 (modified)	GET Default =0	GET Default	GET default	GET default

4.8.3. Different carbon and fuel price/cost

The effect of two other input parameters in the energy systems, carbon, and fossil fuel prices, has been evaluated in the modeling results and how they impact gas turbine application in electricity production. A carbon cost, which is determined in the market, will result from the CAP trading system, but other factors like the industry need or the method for allowance distribution could affect the final price. While changing the CAP will affect the CO_2 price in the market, prediction of the correct price for the future is not possible and accurate; then, different carbon costs will be examined by modifying it directly as a main parameter to check the results independent from the allowance and market prices. On the other hand, future market price prediction based on trading allowances is not possible like in all other markets; modeling based on direct prices could help determine the results independent of the method for determining this price. At the same time, the carbon cost is close to 100 USD/tCO_2 [31], two possible extreme prices of 0 and 500 USD/tCO_2 and a midrange possible price of 200 USD/tCO_2 have been used as different scenarios to check the future effects in the energy market (Cases A3-1 to A3-6, *Table 8*). GET default fuel prices are considered the main input in different modeling scenarios. However, other fuel processes have been used in a few cases to examine possible future results of having different prices for fossil fuels, including NG, oil, and coal. The assumption is that any Fuel price change (increase or decrease) is possible based on market effect, as a measure from policymakers or international political and social changes such as Russia's invasion of Ukraine in 2022. In addition to GET default values for fuels, in a few cases, half and double prices as possible scenarios have been used for fossil fuels. The carbon cost is considered for electricity and industry and, in other cases, for all four sectors.

Table 8. Different carbon and fuel price cases, globally

Case	Description (Changes compared to reference case)
A3-1	C-cost 100 in el. & Industry sectors
A3-2	C-cost 100 for all sectors
A3-3	C-cost 200 in el. & Industry sectors
A3-4	C-cost 200 for all sectors
A3-5	More expensive fossil fuels NG/oil/coal.
A3-6	More expensive fossil fuels & carbon cost 200USD/tCO2 in all sectors

4.8.4. Nuclear, oil, and coal power plant phasing out

As a scenario, policymakers could put limitations or even phase out old power generation technologies, including nuclear, oil, and coal plants. In the coming decades, the significance of nuclear power could be reduced due to the depletion of uranium resources and the increasing role of renewable energy sources [32]. In addition, in a few cases in future energy system modeling, phasing out fossil electricity (oil and coal) has been assumed as a policy in EU ETS. Phasing out coal and oil electricity plants could affect gas turbine position in the future electricity market. In two different cases, phasing out nuclear and fossil-based electricity has been implemented from 2050 (A3-7 and A3-8 in *Table 9*).

Table 9. Nuclear, coal-based electricity phasing out cases in Europe

Case	Description (Changes compared to reference case)
A3-7	Nuclear phase-out till 2050
A3-8	Coal phase-out till 2050

4.8.5. Different Carbon Storage Capacity

Different carbon storage capacities have been examined in parallel with the other default GET parameters. In the IPCC report, 1,000,000 $GtCO_2$ has been predicted as the geological available capacity until 2100 [17]. However, in GET default parameters, it was 2,000,000 (based on the oldest version of the IPCC report). Also, two ultimate limits of 0, as the minimum, and 5,000,000 as the maximum possible scenarios are part of the assumptions (Cases A3-11 and A3-12, in *Table 10*).

Table 10. Different Carbon Storage Capacities

Case	Description
A3 (reference)	Carbon storage capacity =1,000,000 $MtCO_2$
A3-11	Carbon storage capacity =0 $MtCO_2$
A3-12	Carbon storage capacity =5,000,000 $MtCO_2$

4.8.6. Different RES (solar and wind) and Hydrogen penetration

The share of variable renewables, wind, and solar PV is expected to grow significantly in the coming decades; it has become increasingly important to account for their intermittency in large-scale energy models used to explore long-term energy futures [28]. Penetration of solar, wind, and hydrogen energy is assumed in the study to increase by decreasing their CAPEX. By having different CAPEX, the effect of various technology penetration of these renewable energy sources in electricity production will be examined (and maybe other hydrogen applications such as cars and aircraft). The reference model default CAPEX values from the GET have been used. However, other scenarios with doubled and halved values of default CAPEX are used as new inputs to examine the effect of different penetrations. Changing the RES or hydrogen penetration based on the investment cost could directly affect technology development and scale of production. On the other hand, supportive policies and subsidizing could reduce investment costs (Cases A3-21 to A3-24, in *Table 11*).

Table 11. RES and H2 share in electricity production (Different CAPEX).

Case	Description (Changes compared to GET default case)
A3-21	A + more RES share in electricity production (lower CAPEX=0.5 x default GET values)
A3-22	A + more H2 share in electricity production (lower CAPEX=0.5 x default GET values)
A3-23	A + more RES&H2 share in electricity production (lower CAPEX=0.5 x default GET values)
A3-24	A + less RES share in electricity production (lower CAPEX=2 x default GET values)

4.8.7. Different Emission CAP

Based on the latest IPCC report, the maximum cumulative CAP for reaching the climate targets is 500,000 $GtCO_2$ till 2100, and this limit has been used in the reference case. To explore the effect of not having a limited CAP value, a cumulative CAP of 1,700,000 $MtCO_2$ has been applied in the model; in addition, different carbon costs and higher fuel costs are used in other cases to compare the effect of these two measures in the absence of a limited CAP. For carbon costs, values of 100, 200, and 500 USD/tCO_2 and fossil fuels prices (NG, coal, and oil), doubled prices compared to the reference case have been considered. These input values could reveal the importance of having an emission CAP since it seems having carbon costs or expensive fossil fuels could only motivate the electricity industry to decrease the emissions with a CAP as a strict limit. On the other hand, a scenario of 50% less CAP has been considered a more stringent future policy in separate cases -with and without carbon cost- to evaluate how a more limited allowance and CAP could change the electrical technology mix in the future (*Table 12*).

Table 12. Different cumulative CAP tco2

Case	Description (Changes compared to reference case)
A3-90	Smaller CAP (250,000 $GtCO_2$)
A3-91	Smaller CAP (250,000 $GtCO_2$) and Carbon cost of 200 USD/tCO_2
A4	Larger CAP compared to reference case A3 (1,700,000 $GtCO_2$)
A4-1	A4 Case and C-cost 100 USD per tCO_2
A4-2	A4 Case and C-cost 200 USD per tCO_2
A4-3	A4 Case and C-cost 500 USD per tCO_2
A4-4	A4 Case and C-cost 200 USD per tCO_2 and Expensive Fossil Fuel

4.8.8. Different Net Zero target years

During the modeling process, three scenarios have been considered as a target of the Net Zero year, based on the GET model defaults, global agreements, and literature review as possible future global climate policies. In the reference case, 2050 has been set as Europe's Net Zero target year, while 2100 is the global target. In addition, the older global target (including Europe) of 2100 and the possible future global target of 2050 are also examined in this study (*Table 13*).

Table 13. Different NetZero target years

Case	Description
A	Net Zero target year of 2050 for Europe and 2100 for the rest of the world
B	Net Zero target year of 2050 as a Global Target
C	Net Zero target year of 2100 as a Global Target

4.8.9. Efficiency of GT Power Plant

Gas turbine power plants' electrical efficiency (see Equation 1) differs for each type of plant configuration (simple cycle and combined cycle); in the combined cycle, efficiency is higher due to heat energy recovery from gas turbine hot exhaust gases. Electrical output efficiencies for simple cycle and combined cycle as a model output have been obtained from plant simulation results in Thermoflow (*Table 2*). Efficiency has been extracted for both NG and hydrogen fuels for each SC and CC mode. All scenarios in the study have been modeled for simple and combined cycle modes based on the electrical efficiencies from Thermoflow results.

4.9. Sensitivity Analysis

Different important and influential parameters will be checked for sensitivity analysis of the model. Following *Table 14*, parameters that are considered for sensitivity check are listed. Changing the items' values makes it possible to check the changes and trends in the key output parameters, including electricity production by GT using NG and hydrogen as fuel and CCS technology for NG. As was mentioned in the methodology, these items would determine the position and application of gas turbines in the future electricity market.

Table 14. Sensitivity analysis parameters and values.

Parameter	Range	unit
Carbon cost (Constant CAP value of 500,000 $MtCO_2$)	0, 50, 100, 200, 400, 800, 1200	USD/ tCO_2
Emission CAP (No carbon cost)	0, 200, 500, 700, 905, 1250, 1800	$GtCO_2$
Fossil fuel price (coal, oil, NG)	Original input prices will multiply by: 0.5, 1, 1.5, 2, 4, and 5	USD/GJ
Hydrogen to electricity CAPEX (Penetration in electricity production)	Original input prices will multiply by: 0.25, 0.5, 0.75, 1, 1.5, and 2	USD/KW
RES to electricity CAPEX (Penetration in electricity production)	Original input prices will multiply by: 0.25 - 0.5 - 0.75 - 1 - 1.5 - 2	USD/ KW
CO_2, available storage capacity	0, 200,000, 500,000, 1,000,000, 2,000,000, 5,000,000, and 10,000,000	$MtCO_2$

4.10. Method for analysis and discussion of results

Since the study aims for the future gas turbine application in the electricity market under EU ETS scenarios, electricity production by hydrogen and NG will be considered gas turbine application (in simple and combined cycle configurations); also, values for electricity production using carbon capture as a future solution for sustainable gas turbine application using NG, will be under consideration. During the discussion over the modeling results, two main sets of data would be considered as key tools for results analysis:

1. Trends from 2020 to 2100 considering ten years of steps in the modeling process. Trends are important and valuable indicators of changes during the energy transaction in the coming years. They illustrate how the study's key parameters change over time compared to each other based on different policies and technical and market input conditions.

2. Cumulative values for electricity production and carbon captured ($MtCO_2$). As discussed in the model introduction, the modeling process and outputs are based on ten-year time steps; then, for simplification purposes in the study, the cumulative value of parameters are sum-up values for 2030, 2040, ...,2090, and 2100 without considering ten years between. Using the same method for all scenarios makes these parameters a valid indicator for comparing and analyzing results.

On the other hand, the total amount of electricity production by all technologies in Europe is almost the same in different scenarios for 2030 to 2100, then output values related to GT (NG, H2, and NG+CCS) will be directly used for discussion, and comparing purposes (instead of dividing them by total amount of produced electricity with all technologies and converting their share to percentage). In addition, to have an insight into other important and related parameters in the electricity production market, in some cases, cumulative electricity production values (EJ) from nongaseous fossil fuels, including coal and oil, also from RES resources (solar and wind) are presented and discussed if needed.

5. Results and Analysis

This part of the report presents modeling results relevant to this study's scope. Results from the scenarios are compared in separate groups to the reference scenario for analysis purposes and to find the effects of different policies, technical, and economic parameters on outputs. Results compared with other researchers' studies if it was possible. Also, potential needs for future research will be explored. To highlight the future share of gas turbine applications under the effect of EU ETS, the focus is on electricity production statistics in results for the EU region. Based on the assumption of converting combustible gaseous fuels to electricity by gas Turbine, all outputs of electricity production by NG and H2 are considered gas turbine applications for electricity production. In addition, power generation using CCS for NG-fueled GTs is under consideration to evaluate this decarbonization solution for gas turbine power plants. Some more data related to energy transition and emissions in the future (during the study period) is presented in the Appendices. The study's findings could have important outcomes for stakeholders, including policymakers, energy companies, investors, and consumers, considering electricity production by gas turbines in a future energy mix, in parallel with sustainable solutions such as hydrogen fuel or carbon capture. Later in the discussion and conclusion section, a more detailed discussion of the results and future share of gas turbines in the electricity market has been presented under the effect of different EU ETS policies and technical changes. It is essential to consider that during the review and analysis of all results, despite different outputs from various scenarios, all results are based on the model calculations for reaching an optimized energy system by applying different inputs, also considering constraints for achieving the economic and environmental targets. Therefore, regardless of different outputs (values and trends), it should be considered that the energy system would meet the energy demands in all scenarios. In addition, environmental goals would be achieved by the cost-optimized method of the model.

5.1. Overall Review of Results from All Scenarios

This section presents an overall review of results from all modeling scenarios. Results from each case (scenario) provide insights into the future energy mix for Europe, particularly concerning electricity production by nuclear, oil, coal, natural gas, wind, solar, and biofuels. *Figure 9* illustrates the reference case's electricity generation technology mix by primary energy inputs, while the total cumulative electricity production is 199 EJ (as mentioned in the methodology section 4.10, cumulative values are related to the eight output years as model output years). From *Figure 9*, the model provides that the dominant sources of electricity production up to 2050 are uranium and NG, coal, and bioenergy. Renewable energies (hydro, wind, and solar) contribute 35% to 50% of electricity production from 2030 to 2050. Post-2050, there is a substantial increase in the share of solar and wind (defined as

RES in this study) as primary sources of electricity production, accompanied by a significant decline in the contributions from uranium and natural gas. After 2050, electricity production from main CO_2 emitters will be combined with a carbon capture solution as a sustainable method for following emission reduction policies due to model constraints. A minor portion of power generation, starting from 2070, stems from hydrogen (GT application), displaying a rising trend over time. The future electricity mix for all other scenarios has been presented in Appendix 02, electricity production technology mix in Europe, since our focus in the study is mostly on parameters that are indicators of gas turbine application, mainly hydrogen, and NG as fuels. Also, CCS has been reviewed as a complementary technology and an option for decarbonizing gas turbine power plants.

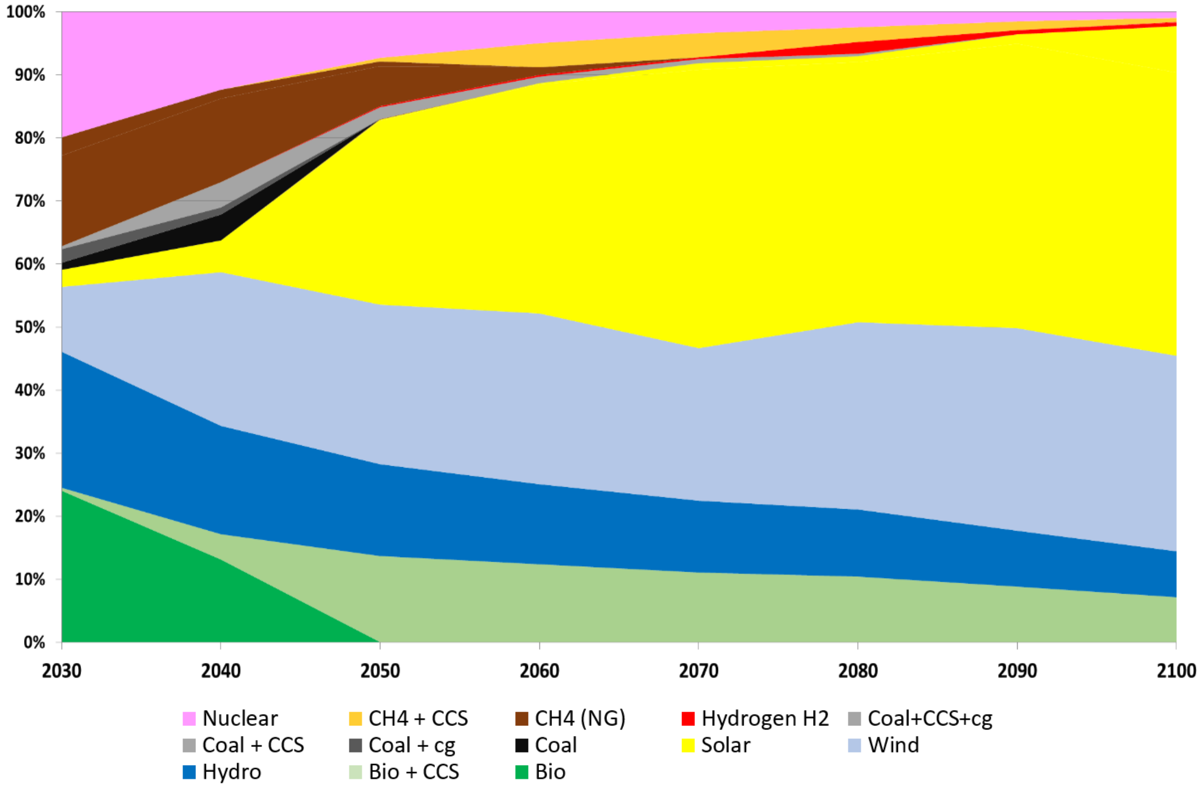

Figure 9. European electricity technology mix for the reference case

(Cumulative electricity production is 199EJ for output years in the model; see section 4.10.)

In *Figure 10,* cumulative values for electricity production from GT have been presented for all scenarios, while gray bars show total electricity production by NG fuel (plant with and without CCS), green bars are the electricity production share using CCS for NG-fueled plants, and red bars are electricity production using hydrogen as a carbon-free GT fuel. The first significant outcome from this graph is higher electricity production -higher share- of gas turbines in combined cycle (CCPP) compared to single cycle (SCPP)mode. Higher participation of CCPP is recognized by significantly high electricity production from NG, compared to simple cycle values in the bar chart.

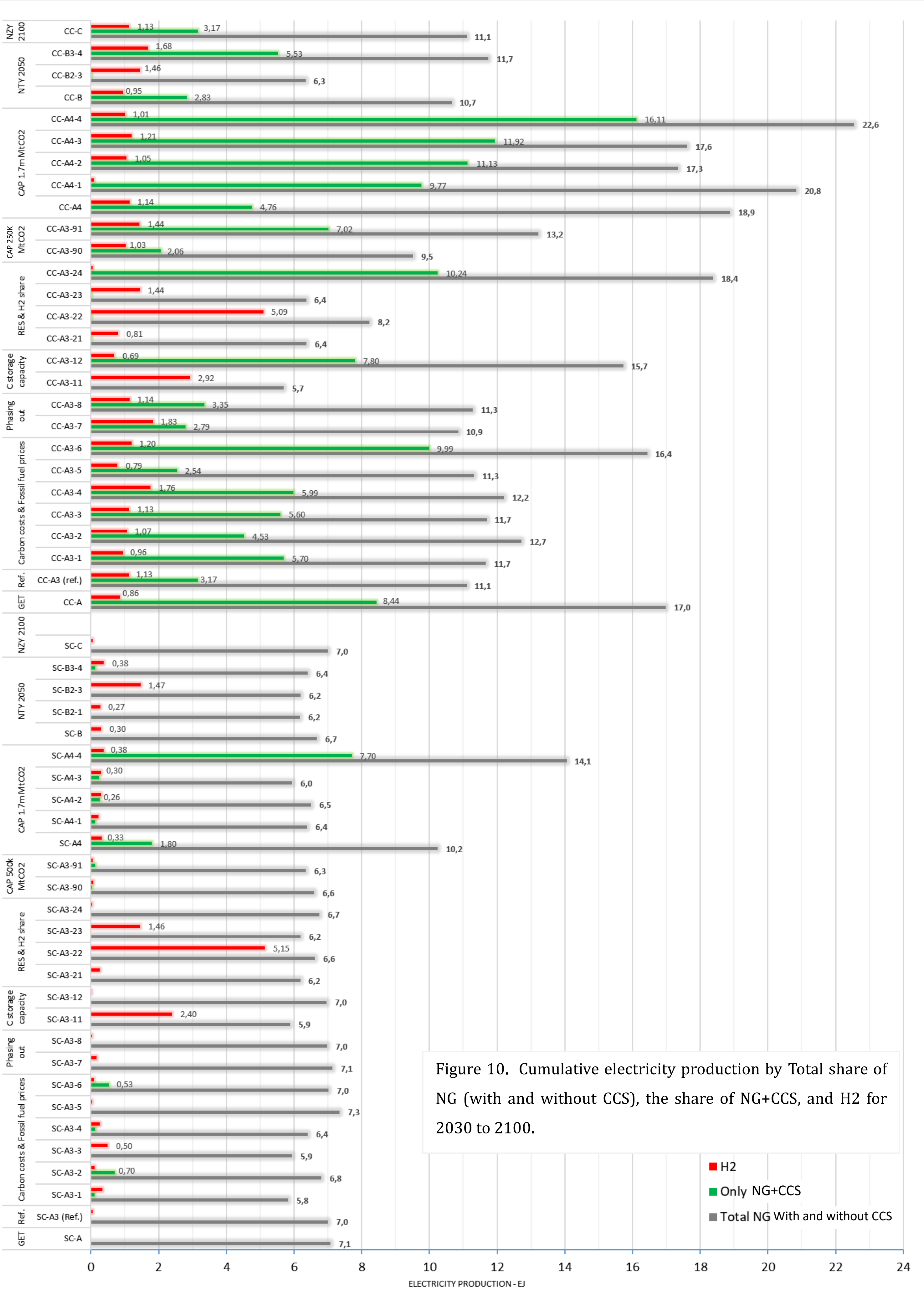

Figure 10. Cumulative electricity production by Total share of NG (with and without CCS), the share of NG+CCS, and H2 for 2030 to 2100.

In addition, the share of electricity production with GT using sustainable solutions is higher in CCPP, including hydrogen as primary fuel and carbon capture technology for NG-fueled GT plants. The larger share of electricity production in CCPP results from higher electrical efficiency (see *Equation* 1) of the combined cycle compared to the simple cycle. For the simple cycle mode, only in the scenario with the large emission CAP Compared to the reference (Cases A4-1 and A4-4), gas turbine application share is more than other scenarios, mainly using NG as fuel, specifically when the carbon cost and fossil fuel prices are higher, and this is due to the possible shift from coal and oil to NG as a fuel. Unlike SCPP, in all combined cycle cases, hydrogen has a considerable share (Up to 5 EJ of cumulative electricity) as a main fuel for GT combustion. In the scenarios with low hydrogen production costs, which means high hydrogen penetration, and the case with zero carbon storage capacity, hydrogen is a significant source of electricity production up to 5EJ cumulative electricity production.

Table 15 holds average values of cumulative electricity production in all scenarios for gas turbines (hydrogen and NG sources) in both simple and combined cycles, which shows a larger share of combined cycle mode for all similar cases. Another outcome from this table, in addition to the higher share of GT in CCPP mode, is carbon capturing and storage values. CCS has the same values for both SCPP and CCPP. This shows that overall, CCS would be the same in the electricity technology mix and the importance of CCS technology regardless of different scenarios in the future. As can be extracted from the table, carbon capturing values are considerably higher than carbon storage in the whole electricity market for both plant configurations. However, this is not included in the scope of this study; it could be a critical area for more research about methods for handling extra captured CO_2 compared to stored value and a deeper study for the limited value of stored carbon.

Table 15. Average cumulative electricity production, capturing, and storage for all scenarios 2030-2100.

Gas turbine plant configuration	GT with hydrogen fuel (EJ)	GT with NG fuel (EJ)	GT with NG fuel and capturing technology (EJ)	Average of cumulative carbon captured in the electricity market ($GtCO_2$)	Average cumulative carbon stored in the electricity market. ($GtCO_2$)
simple cycles	0,54	7	0.4	69.1	12.5
combined cycles	1,37	12,5	5.4	74,9	13

Considering the more significant share of combined cycle plants with gas turbine technology in the results, in the following sections, only results from combined cycle scenarios have been presented during the results review and analysis. This will prevent presenting a wide range of output data and trends related to single-cycle GT plants with less possibility in the modeling outputs.

The final target for all EU ETS policies and all technological improvements and studies is achieving the desired CO_2 concentration in the atmosphere and preventing global warming. *Figure 11* shows atmospheric concentration during the study period as a modeling output for reference scenarios. In addition, the emissions trend in Europe in the reference scenario is demonstrated in *Figure 12.* Emission trends for the two other regions are also given in the same graph for comparison purposes (NAM: north America, PAS: Pacific Asia). Similar Trends for some other scenarios are presented in the Appendices.

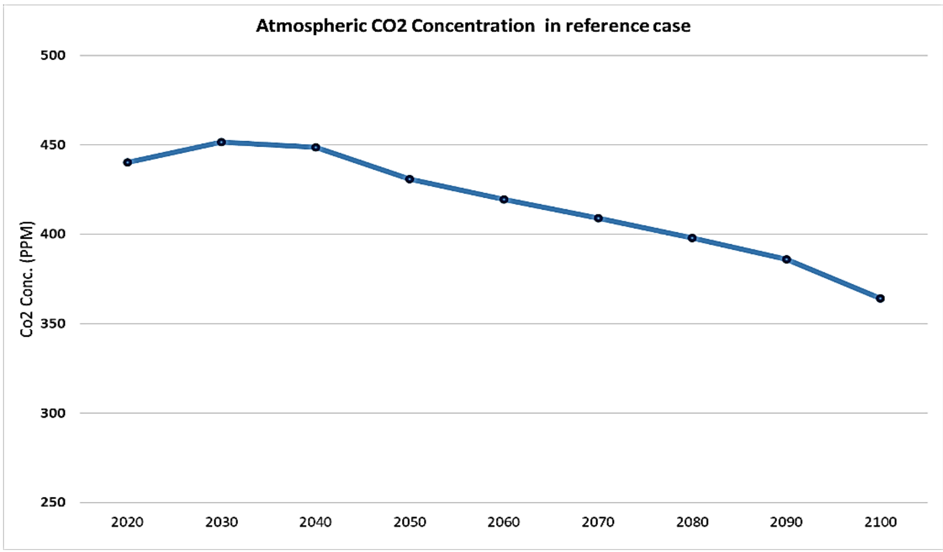

Figure 11. Atmospheric CO_2 concentration trends for reference scenario (2020-2100)

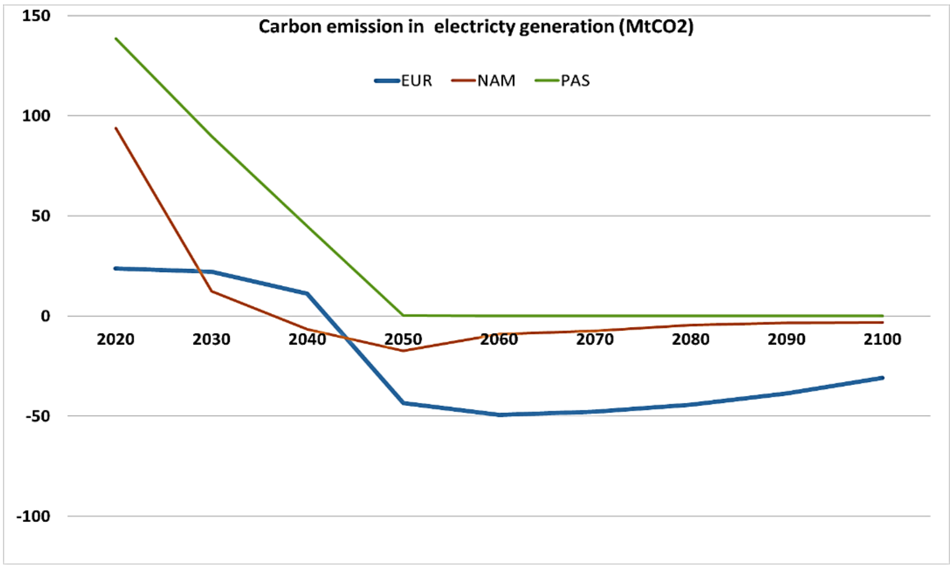

Figure 12. Emission trend in Europe for reference scenario (2020-2100),
(Two other regions are given for comparison, NAM: north America, PAS: Pacific Asia).

5.2. Comparing GET with default inputs and Reference case

This section presented the results of running the model with GET default inputs (Case A) and outputs from reference cases -with updated input parameters- (Case A3). As it was mentioned in the methodology section, three different inputs have been updated based on new literature:

- Cumulative emission CAP has been decreased to 500,000 $MtCO_2$ (700,000 in the default GET values),
- Geological available capacity for carbon storage has changed to 1,000,000 $MtCO_2$ (2,000,000 in GET default inputs),
- The Net Zero emission target year has been updated to 2050 for Europe, while it was 2100 in the GET default parameters.

As a result of having the GET default input values, the total share of electricity production by GT is more considerable in Europe (Table 16) compared to reference cases. This result is due to the higher value of emission CAP, larger carbon storage capacity, and more extended period for decreasing the emission. However, electricity from H2 in the reference case is higher than the GET default results. This is based on having smaller CAP (more limit on carbon emitter plants), less CO_2 storage capacity in the reference mode, and more need for sustainable fuels for GT. This result is in parallel with higher RES share and lower electricity from fossil fuels in the reference case compared to the GET default scenario. It highlights the importance of the three updated parameters and their effect on the model outputs and future electricity technology mix.

Table 16. Electricity production (EJ) in the GET model based on different technologies.

Scenario code	Electricity production (EJ) by primary fuel/resource						
	H2 (GT)	NG(GT)	NG+CCS (GT)	Total from GT plants (H2, NG, NG+CCS)	RES	Coal, oil	All resources
CC-A3 (ref.)	1,13	7.94	3.17	12.2	125.7	3.3	201
CC-A (GET defaults)	0.86	8.54	8.44	17.8	106.2	5.4	188
SC-A3 (Ref.)	0.04	6.99	0,0	7.0	129	4	190

As a comparison between output trends, electricity production by hydrogen fuel and CCS technology for NG fuel are demonstrated in *Figure 13.* The trend of electricity production by hydrogen is increasing in both cases (reference and GET default inputs). Still, as mentioned earlier, it has a much higher cumulative value – as an area under the curve- in the reference case due to more restricted policies and lower carbon storage capacities. On the other hand, the same reasons lead to a sharp upward trend of electricity production using NG and CCS technology with GET default parameters.

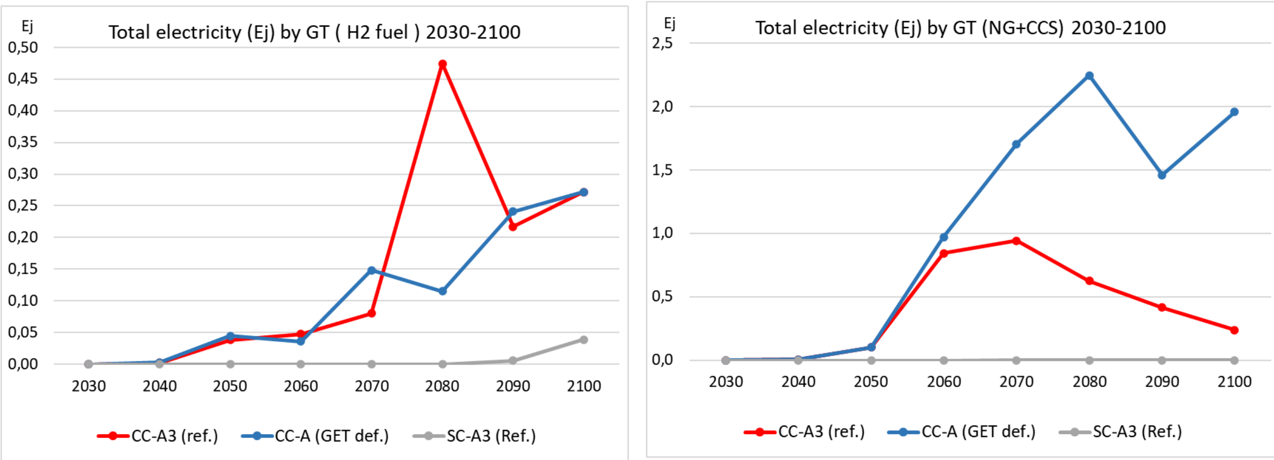

Figure 13. Electricity production trends by GT in different scenarios and configurations

5.3. Carbon Cost and Fossil Fuel Price

This section reviews the results for modeling scenarios with different carbon costs and higher fossil fuel prices, while both conditions could be potential future scenarios of EU ETS policies or as market conditions. The results of having different prices for CO_2 and more expensive fossil fuels are demonstrated in *Figure 14* and *Figure 15*. From 2030 to 2100, electricity production by GT has a decreasing trend for all scenarios after a few fluctuations in values and a peak in 2040. The only case with higher electricity production by GT is A3-6, the scenario with a combination of a higher carbon cost - 200 USD/tCO_2 - and more expensive fossil fuels, compared to the reference case. This case significantly differs from other cases in this section in trends and cumulative values graphs. Following the A3-6, the carbon cost of 200 USD/tCO_2 and 100 USD/tCO_2 (for all sectors) have the maximum values for electricity generation using GT in both trends and cumulative values compared to other cases and reference scenario. Scenario A3-4, with a high carbon cost of 200 USD/tCO_2, has the maximum values of electricity production with hydrogen and with capturing technology for NG fuel after A3-6 in both trends and cumulative graphs. In addition, based on *Figure 14* and *Figure 15*, carbon capture technology is higher in all cases with carbon cost compared to the reference case. On the other hand, having more expensive fuel than reference mode leads to even less electricity from hydrogen or CCS technology. With higher fossil fuel prices -without carbon cost- NG fuel for GTs (without CCS) substitutes electricity from fossil fuels in old generation plants and hydrogen fuel in the GT power plants. As analysis for fuel and carbon cost scenarios, it is possible to argue that higher fuel cost without carbon pricing does not affect GT application in the future compared to the reference case. These results highlighted the effect of carbon pricing in all sectors for future GT share in the electricity market, leading to more CCS and hydrogen applications as sustainable solutions for GTs (*Table 17*).

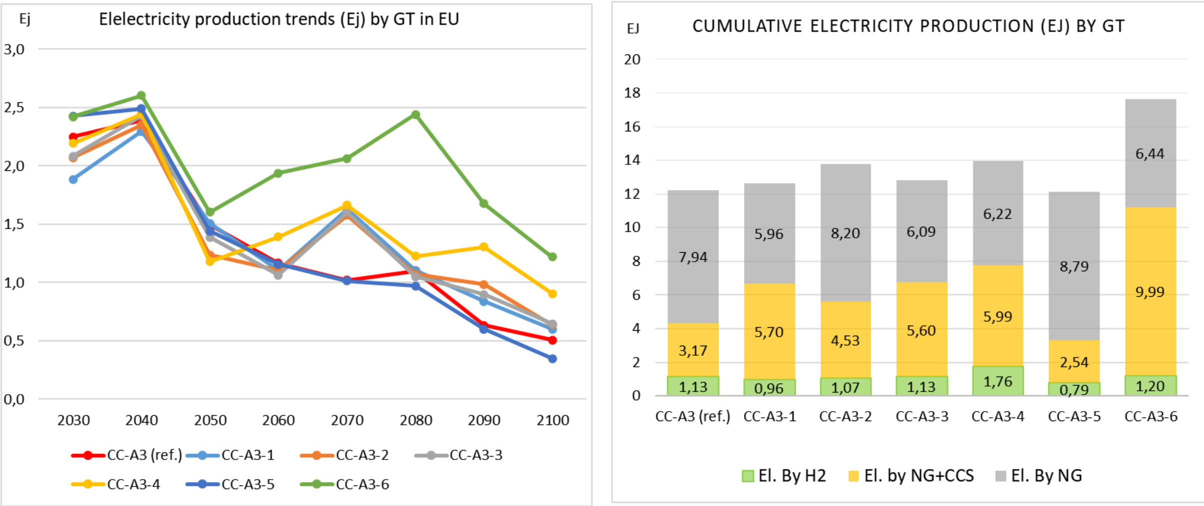

Figure 14. Electricity production trends and cumulative production using GT.

-A3 (Ref.)	Reference case, CAP=500 GtCO2 & Storage=1m MtCO2
-A3-1	C-cost 100 in el. & industry sectors
-A3-2	C-cost 100 for all sectors
-A3-3	C-cost 200 in el. & industry sectors
-A3-4	C-cost 200 for all sectors
-A3-5	Expensive fossil fuels (coal and oil)
-A3-6	Expensive Fossil + C-cost 200 (all sect)

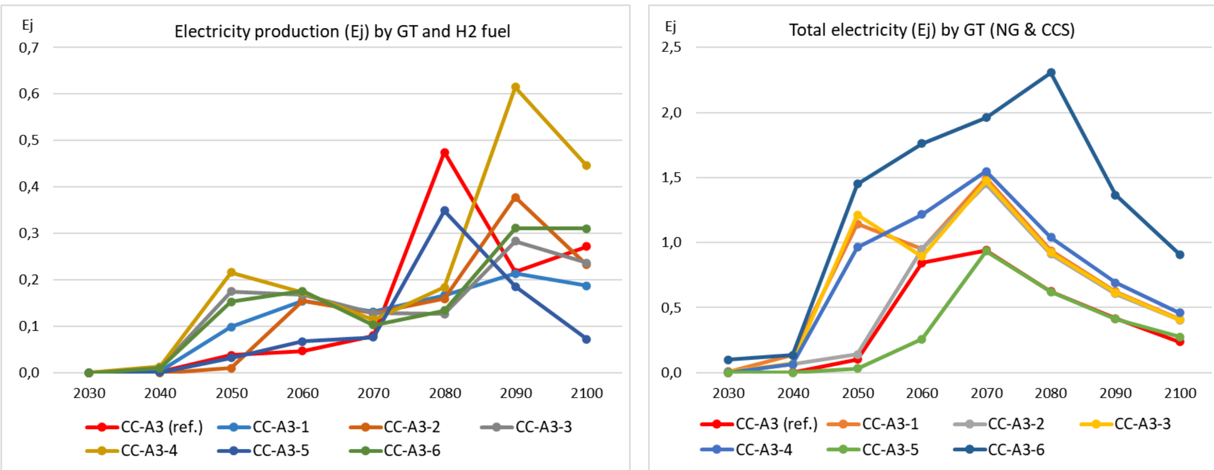

Figure 15. Electricity production trends and cumulative productions by GT using H2 or NG+CCS.

Table 17. Electricity production (EJ) in scenarios with different carbon costs and higher fuel prices.

Case Code	Electricity production (EJ) by primary fuel/resource						
	H2 (GT)	NG(GT)	NG+CCS (GT)	Total GT (H2, NG, NG+CC)	RES	Coal, oil	All resources
CC-A3 (ref.)	1.13	7.94	3.17	12.2	125.7	3.3	201
CC-A3-1	0.96	5.96	5.70	12.6	114.9	6.8	193
CC-A3-2	1.07	8.20	4.53	13.8	115.2	9.8	197
CC-A3-3	1.13	6.09	5.60	12.8	112.1	2.7	188
CC-A3-4	1.76	6.22	5.99	14.0	117	2.1	195
CC-A3-5	0.79	8.79	2.54	12.1	121.1	2.2	196
CC-A3-6	1.20	6.44	9.99	17.6	116.5	1.6	198

5.4. Different Emission CAPS

This section discusses results from scenarios with different CAP values as input parameters compared to the reference case. While in the reference, the CAP value is 500,000 $MtCO_2$, in this section, a higher value of 1,700,000 $MtCO_2$ -representing less restriction- and a smaller value of 250,000 $MtCO_2$ for CAP -as a stricter policy- are examined. As illustrated in *Figure 16*, GT application for power generation is upward in all cases with larger CAP (All A4 cases), and they have decreasing trends in the case of smaller CAP (A3-90, A3-91). Trends for the share of hydrogen as a GT fuel are increasing in all cases (*Figure 17*) but not much more than reference cases considering cumulative value (*Figure 18*), while the application of carbon capture technology for NG as fuel is expanding in all cases except for cases with lower CAP compared to the reference. Lower CAP leads to higher RES and more H2 share. It is possible to highlight the importance of carbon cost in the case of having higher CAP, which leads to more shares of C and H2 despite a slight decline in the cumulative share of GT in the market. Less CAP leads to a more than 2 EJ decrease of cumulative electricity by GT and 1 EJ decline of fossil-based electricity (*Table 18*) compared to the reference case, while these values have compensated with increasing electricity generation from RES by more than 8 EJ more than the reference case.

Table 18. Electricity production (EJ) considering different CAP.

Case Code	Electricity production (EJ) by primary fuel/resource						
	H2 (GT)	NG(GT)	NG+CCS (GT)	Total GT (H2, NG, NG+CC)	RES	Coal, oil	All resources
CC-A3 (ref.)	1.13	7.94	3.17	12.2	125.7	3.3	201
CC-A4	1.14	14.13	4.76	20.0	88.4	15.6	176
CC-A4-1	0.09	11.08	9.77	20.9	89.1	16.4	187
CC-A4-2	1.05	6.22	11.13	18.4	99.1	7.7	187
CC-A4-3	1.21	5.70	11.92	18.8	101.8	13	194
CC-A4-4	1.01	6.44	16.11	23.6	101.5	4.4	191
CC-A3-90	1.03	7.46	2.06	10.5	133	2.3	206
CC-A3-91	1.44	6.21	7.02	14.7	127	2	204

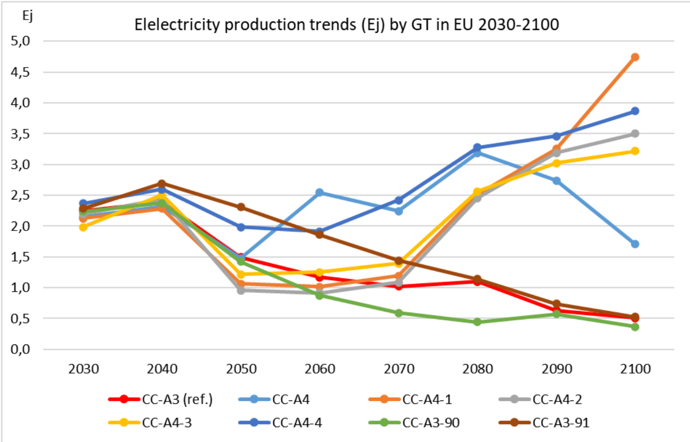

Figure 16. Electricity production by GT with different emission CAPs scenarios

-A3 (Ref.)	Reference case, CAP=500 GtCO2 & Storage=1m MtCO2
-A3-90	A3 and lower cumulative CAP 250Gt
-A3-91	A3(ref.) + CAP 250 + C-cost 200 (all sec)
-A4	Larger CAP compare to A3
-A4-1	A4 + C-cost 100 (all sect.)
-A4-2	A4 + C-cost 200
-A4-3	A4 + C-cost 500
-A4-4	A4 + C-cost 200+ exp. Fuel

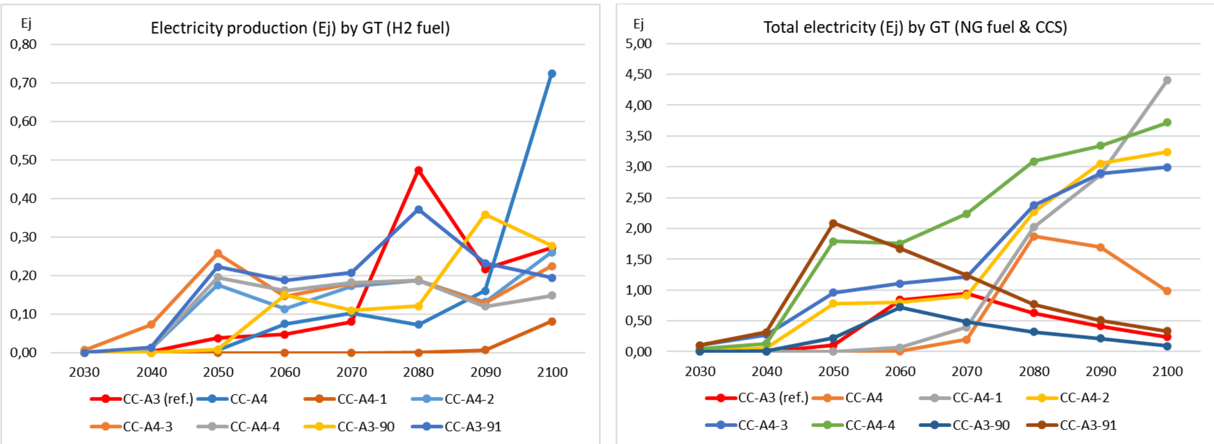

Figure 17. Electricity production trends by H2 and NG+CCS in GT plants and different CAP cases

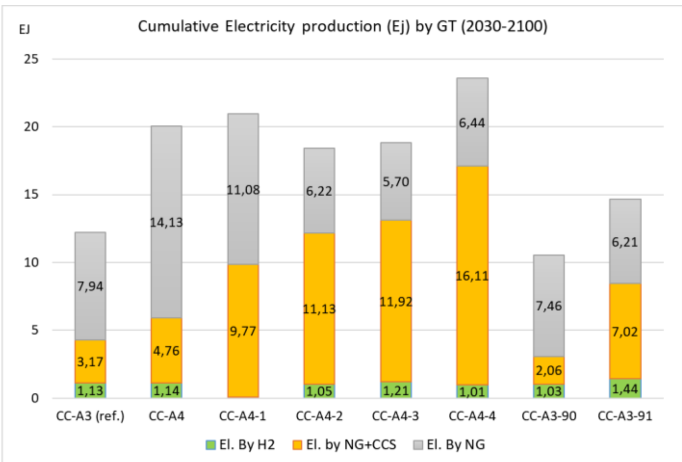

Figure 18. Cumulative electricity by GT for different CAP cases

5.5. Different Net Zero year

Comparing results in the reference scenario with two other cases with different Net Zero emission target year strategies did not reveal any significant change in the value of electricity production by GT plants considering the trends or cumulative values of electricity production, while the share of CCS system or H2 fuel is also almost the same as the reference case (*Figure 19* and *Figure 20*). Having 2050 as a Net Zero target year with more RES and H2 penetration (Case B2-3) leads to a significant decrease in GT. However, the share of electricity by H2 increased compared to the reference mode. In the case of the same year -2050- as the Net Zero target, adding a carbon tax (Case B2-4) leads to a considerable rise in the share of H2 and CCS technology for GT plants. Two important results here are the effect of more RES on decreasing the total share of electricity from GT and the effect of higher carbon cost on increasing the share of CCS and H2.

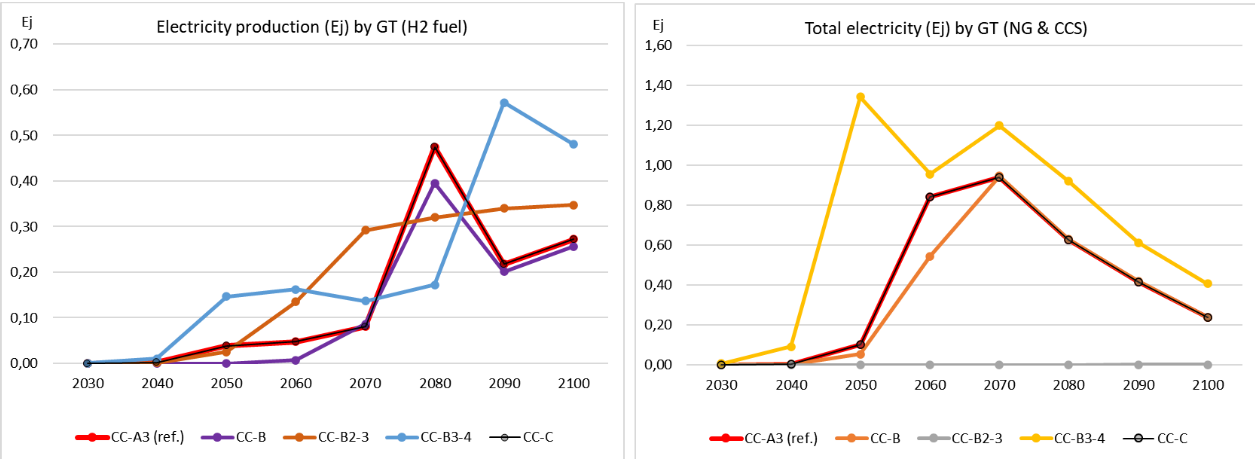

Figure 19. Share electricity in GT plants with hydrogen fuel and CCS technology for NG.

-A3 (Ref.)	Reference case, CAP=500 GtCO2 & Storage=1m MtCO2
-B	A3(ref.) + Global Net Zero year of 2050
-B2-3	B + more RES&H2 penetration
-B3-4	B + C-cost 200 (all sectors)
-C	A3(ref.) + Global Net Zero year of 2100

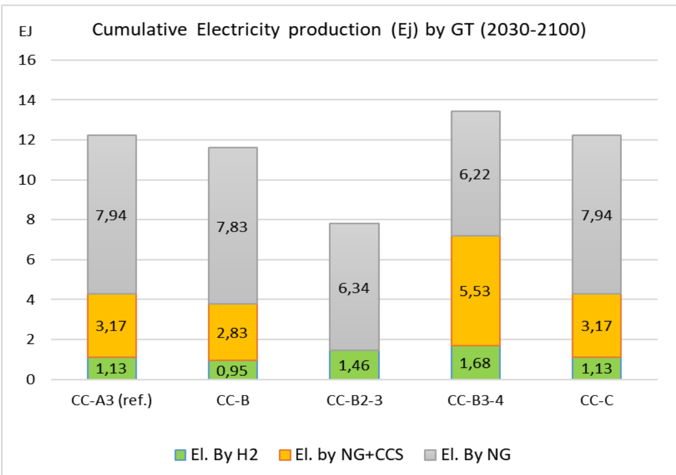

Figure 20. Cumulative electricity by GT regarding different Net Zero target years

5.6. Phasing out Nuclear and Coal Electricity

Results of the cumulative share of GT considering phasing out nuclear electricity plants (A3-7) and phasing out the coal-fired plants (A3-8) until 2050 do not show a significant effect on the share of GT in electricity production (*Figure 21*), compared to the reference. However, phasing out nuclear plants (A3-7) leads to a larger share of electricity from H2-fueled GTs and cumulative electricity production by GT. The cumulative share of electricity by GT using H2 increased from 1.13 EJ to 1.83 EJ. In the case of Phasing out coal, electricity production could be compensated by nuclear (*Figure 22* - Right side), while phasing out nuclear compensated with more electricity production using hydrogen as a carbon-free fuel for GTs (*Figure 22* - Left side). As a conclusion for this section, it could be mentioned that phasing out nuclear from the electricity technology mix in the future could lead to more application of hydrogen fuel as a solution for more sustainable GT share while phasing out coal will not lead to a meaningful increase for GT plants.

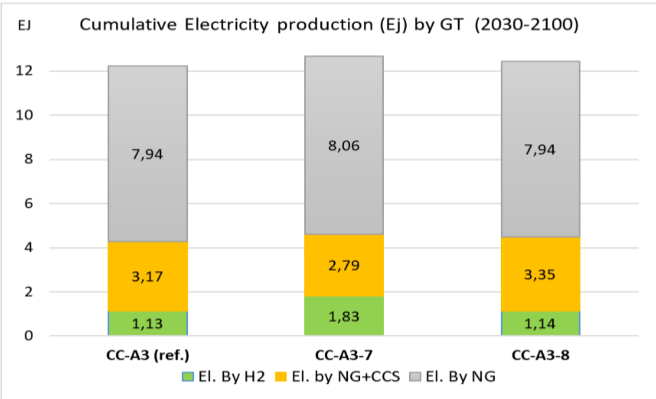

Figure 21. Cumulative values for electricity by GT

-A3 (Ref.)	Reference case, CAP=500 GtCO2 & Storage=1m MtCO2
-A3-7	Nuclear phase out until 2050
-A3-8	Coal phase out until 2050

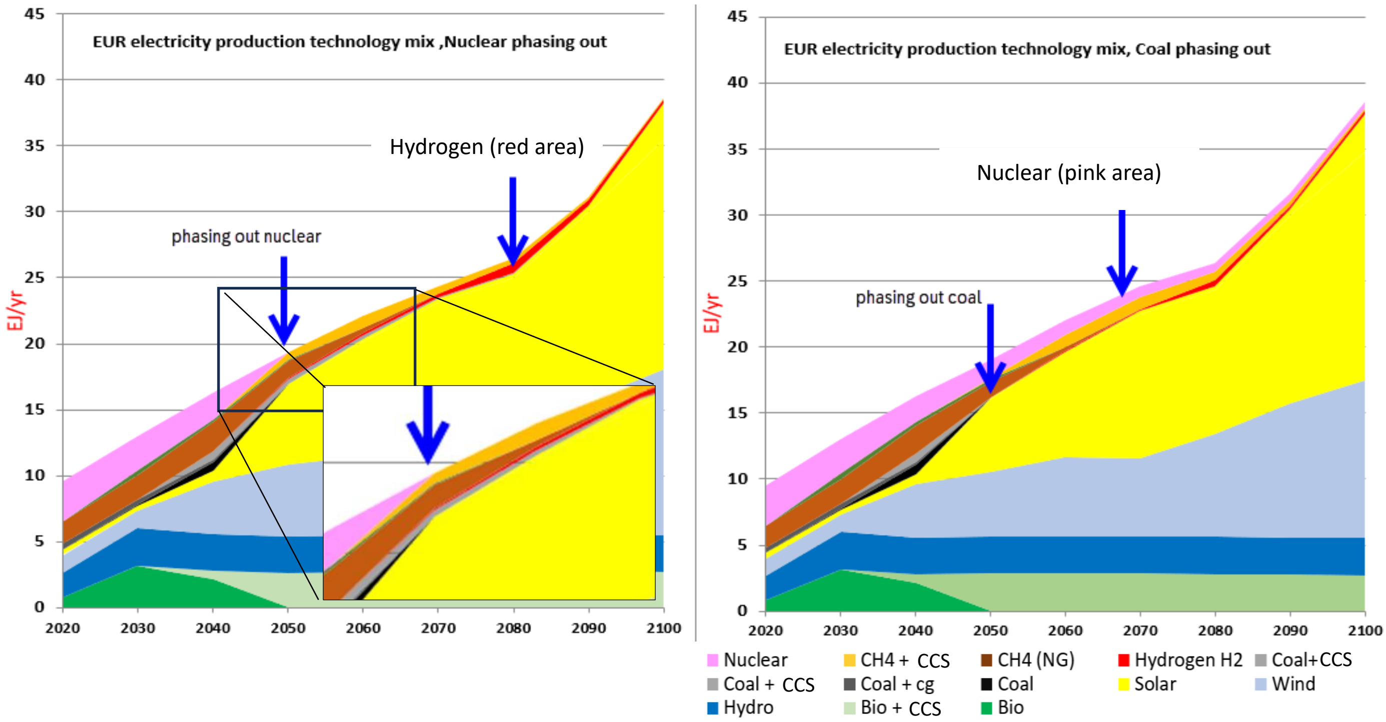

Figure 22. Electricity technology mix and phasing out nuclear (left side) and phasing out coal (right side)

5.7. Different RES and Hydrogen Penetration

Results in this section revealed more electricity share using hydrogen as GT fuel (A3-22) in case of higher H2 penetration based on the lower investment costs (*Figure 23* left side); also, in cases with lower RES penetrations (A3-24), there is a considerable increasing trend for a share of GT using NG and CCS technology (*Figure 23* right side). These results confirm the study assumption of higher penetration for H2 and RES in case of decreasing investment costs. On the other hand, more RES penetration (A3-21 and A3-23) leads to less GT application since producing electricity from cheap RES is more reasonable, and only a small capacity of GT plants will be used to balance RES's intermittency. In the opposite scenario, lower RES penetration leads to more electricity by NG-fueled GTs utilizing CCS systems and less hydrogen fuel due to a lack of cheap electricity from RES for electrolyzers. As illustrated in *Figure 24*, the GT application has a faster decline by having more RES penetration with lower investment costs (A3-22 and A3-23) compared to the reference case.

Results in this section reveal less share of GT in the future by having cheaper RES, but almost the same share of H2 -as the reference case- which seems necessary for managing RES intermittency and shaving the demand peaks by burning hydrogen in GT. Also, cheaper hydrogen but not cheap RES leads to a significant increase in electricity production using GT with H2 fuel. Finally, higher RES costs (less participation) lead to higher GT applications using NG and CCS (Not H2).

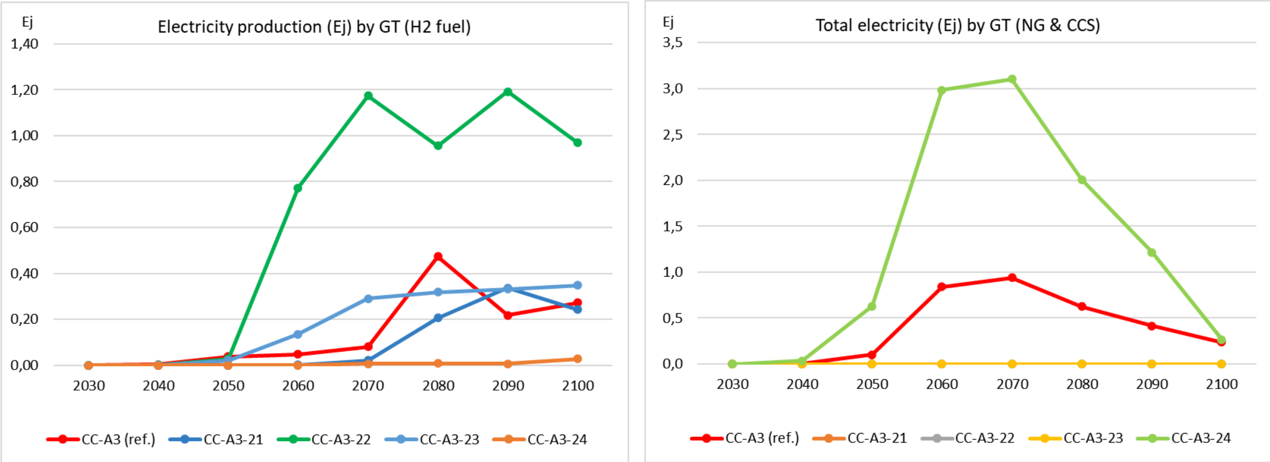

Figure 23. Trends for electricity production using H2 and CCS in GT plants.

-A3 (Ref.)	Reference case, CAP=500 GtCO2 & Storage=1m MtCO2
-A3-21	A3(ref.) and more RES penetration
-A3-22	A3(ref.) and more H2 penetration
-A3-23	A3(ref.) and more RES and H2 penetration
-A3-24	A3(ref.) and less RES penetration

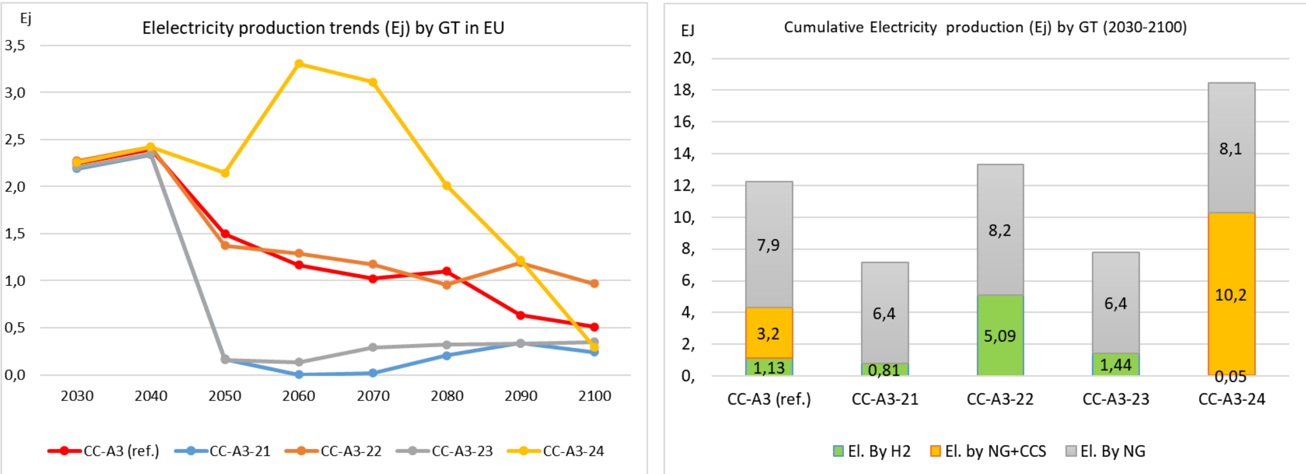

Figure 24. Cumulative values for electricity by GT

5.8. Available Carbon Storage Capacities

By having less carbon storage capacities (Here A3-11 with Zero capacity), electricity production using H2 as GT fuel has more increasing rate in trends (*Figure 25,* left side), while having more carbon storage capacities (Cases A and A3-12) leads to higher increasing trends for power generation using NG and CCS technology (*Figure 25,* right side) in addition to more upward trends of total electricity by GT in comparison with reference case or zero capacity (*Figure 26,* left side).

As a conclusion of analysis results in this section, it is possible to argue that higher carbon storage capacity leads to more GT participation with higher electricity production using CCS, and lower capacities lead to lower cumulative GT application but more share of H2 compared to reference case (*Figure 26,* right side).

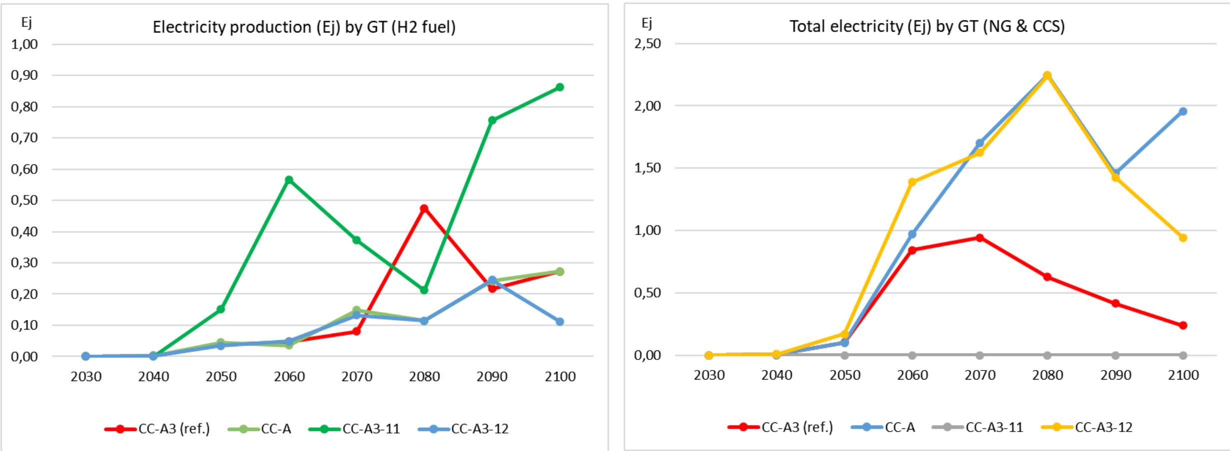

Figure 25. Electricity production trends using H2 and CCS for GT plants.

-A	GET model default input values C-storage=2m MtCO2
-A3 (Ref.)	Reference case, CAP=500 GtCO2 & Storage=1m MtCO2
-A3-11	A3(ref.) and Carbon storage =0
-A3-12	A3(ref.) and Carbon storage =5m MtCO2

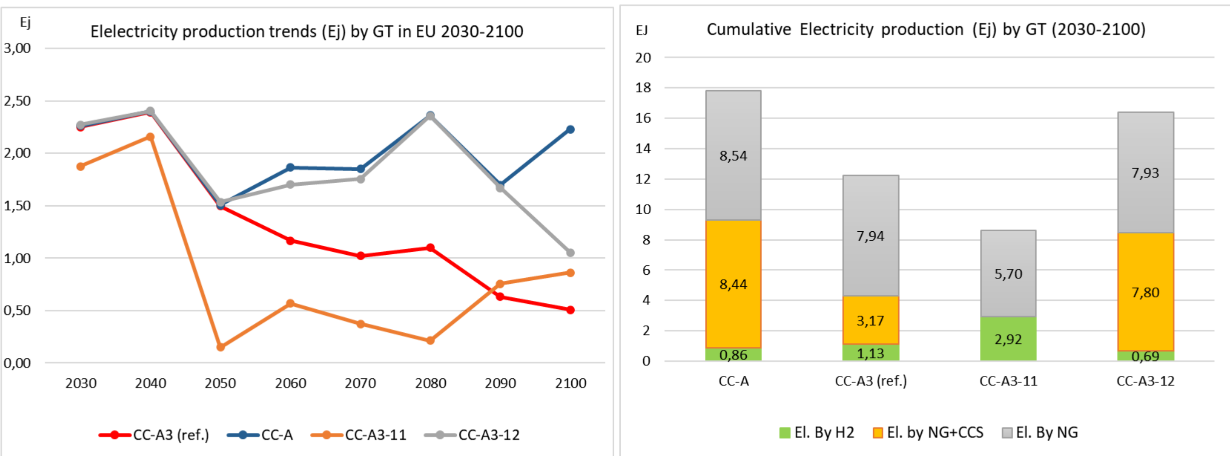

Figure 26. Electricity production by GT and cumulative production for different CCS capacities

5.9. Sensitivity analysis

Results and analysis for the sensitivity of model outputs to a broader range of input variables are presented for reference case (A3) in simple cycle mode to review and control each input parameter's effect within a more extensive range of values. The modeling outputs under consideration in this section are the total electricity production by GT (using NG, NG+CCS, and H2), electricity by only NG, by NG+CCS, and hydrogen as different outputs. Important parameters that will be changed as model input variables are described in the methodology and different values assigned to them are mentioned in *Table 14*. In this sensitivity analysis section, a simple cycle configuration is selected to review the effect of different ranges of parameters directly on the GT output results and not on a plant with extra equipment, which increases overall efficiency in sensitivity analysis. It is important to consider the GT behavior as a single equipment in the study.

5.9.1. Sensitivity to Carbon Emission Price

Based on other literature, while the total emissions (all sectors and all fuels) keep growing, implementing a \$100/tCO_2 tax can only reduce the emission growth rate and will not lead to a declining trend of CO_2 emission [13]. In another research, there was a relation between carbon cost, allowance, and emission CAP; as a result, emission decreased by more limits on allowance -decreasing CAP- while emission price increases [3]. This section discusses the sensitivity of model outputs under the effect of increasing carbon cost. As demonstrated in *Figure 27,* with increasing carbon emission price, the cumulative share of total electricity from GT plants increased to 12 EJ at 400 USD/tCO_2 and then decreased. The trend of electricity by GT using NG follows the same pattern. Still, the trend for electricity from NG-fueled GT using CCS technology increased sharply from 0 EJ to 3.5 EJ. In comparison, the trend for H2 demonstrates a small share of hydrogen and not more than 0.3 EJ; a more detailed chart with a different scale for the share of H2 (*Figure 28*) reveals a growth of 5 to 6 times for electricity from H2 for higher carbon costs (0.04 EJ in the reference case and more than 0.25 EJ in C-costs more than 400 USD/tCO_2). Results in this part show a considerable effect of carbon cost on GT application using NG and considerable expansion of CCS and H2 application in GT-based power plants compared to reference.

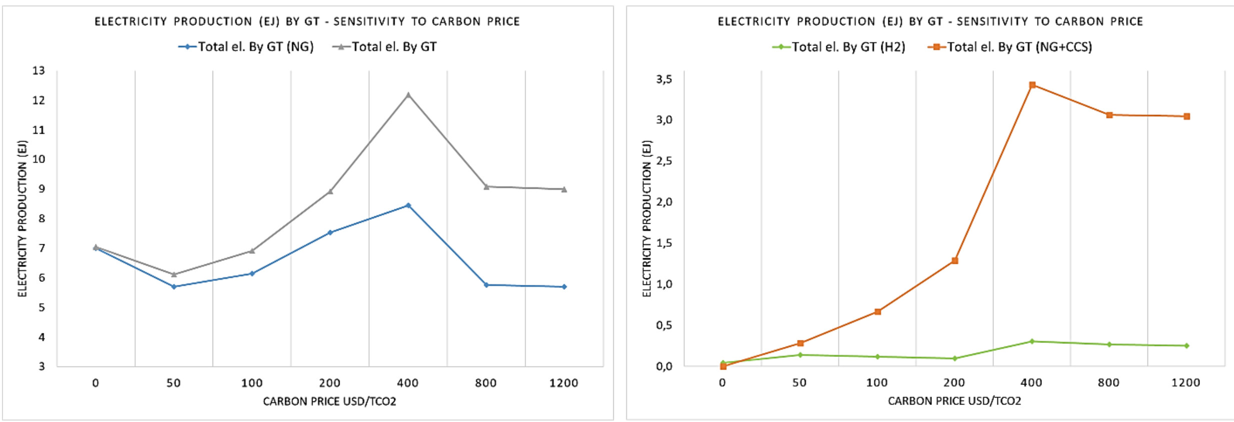

Figure 27. Electricity production trends (EJ), by GT and sensitivity to the carbon cost

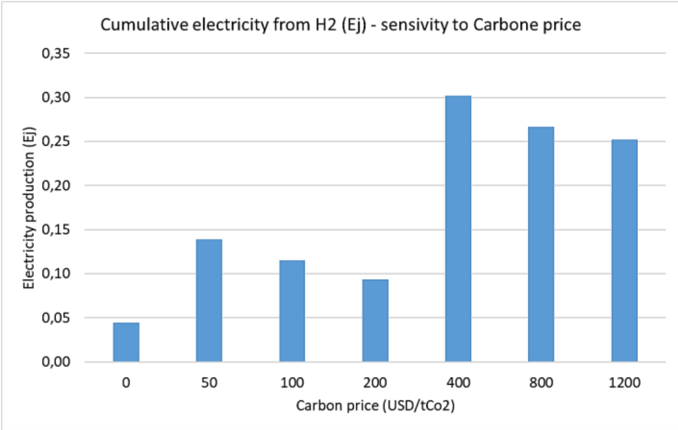

Figure 28. Cumulative electricity production of GT using H2 as fuel.

5.9.2. Sensitivity to Emission CAP

Increasing emission CAP means removing one of the critical measures for controlling emissions of different sectors. In this section, results of different values for emission CAP on electricity production by GT are demonstrated for reference case while carbon cost is zero. As illustrated in *Figure 29,* By increasing emission CAP, the application of GT has an overall increasing trend from 7.5 EJ to 11 EJ; However, the trend increasing rate is not high for CAP up to 1250 $MtCO_2$, it has a considerable jump to 11 EJ between CAP 1250 and 1800 $MtCO_2$. Trends for NG using CCS and H2 are demonstrated in *Figure 30*; when electricity production from H2 has a decreasing trend by expanding the CAP, the share of NG using CCS is zero in most cases. The effect of increasing CAP in electricity production from fossil fuels (oil and coal) is demonstrated in *Figure 31*; by having higher CAP, it is more economical to use fossil fuel for electricity generation, and in the maximum value of 1,800,000 $MtCO_2$, cumulative electricity from fossils is 17 EJ for output years compare to 10EJ from GT using NG. It seems that the GT application using NG+CCS and H2 has a significant increase with CAP of 1,800,000 $MtCO_2$ to make it possible for coal and oil electricity as a cheaper option to expand more (*Figure 31*) and make use of this capacity for releasing emissions to the atmosphere. *Figure 31*, right side, presents the RES decreasing trend by expanding CAP values. As could be expected by increasing the CAP as one of the essential measures in the EU ETS, applying all fossil fuels (including GT with NG fuel) will considerably increase, while sustainable solutions such as RES and H2 fuel decline.

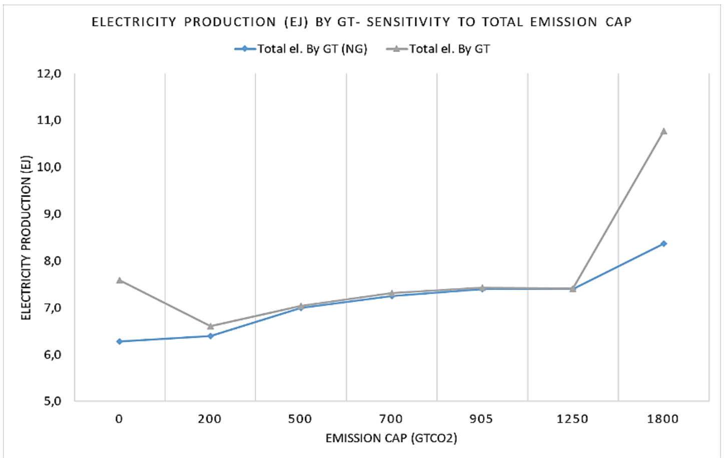

Figure 29. Electricity production trends (EJ), by GT and sensitivity to emission CAP

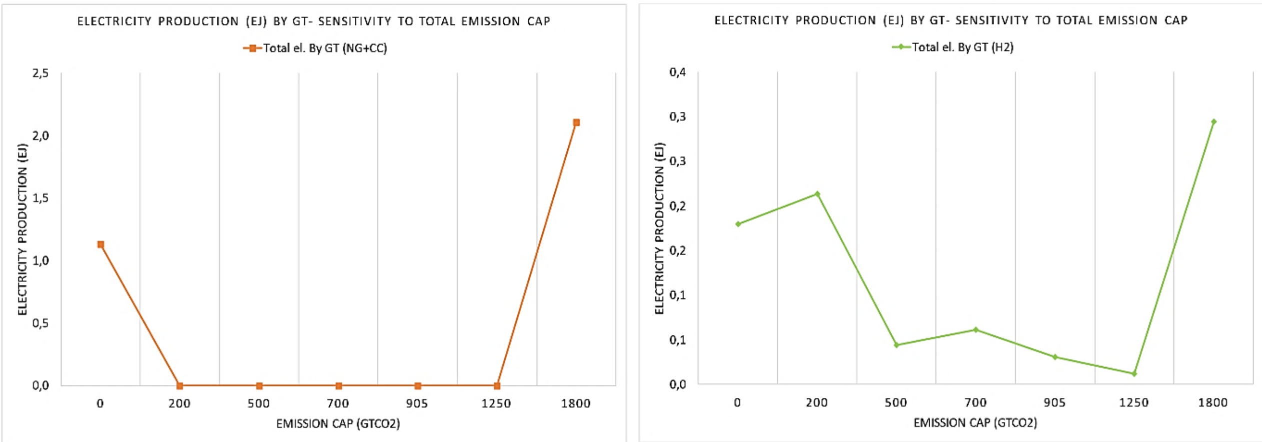

Figure 30. Electricity production trends (EJ), by GT and sensitivity to the emission CAP

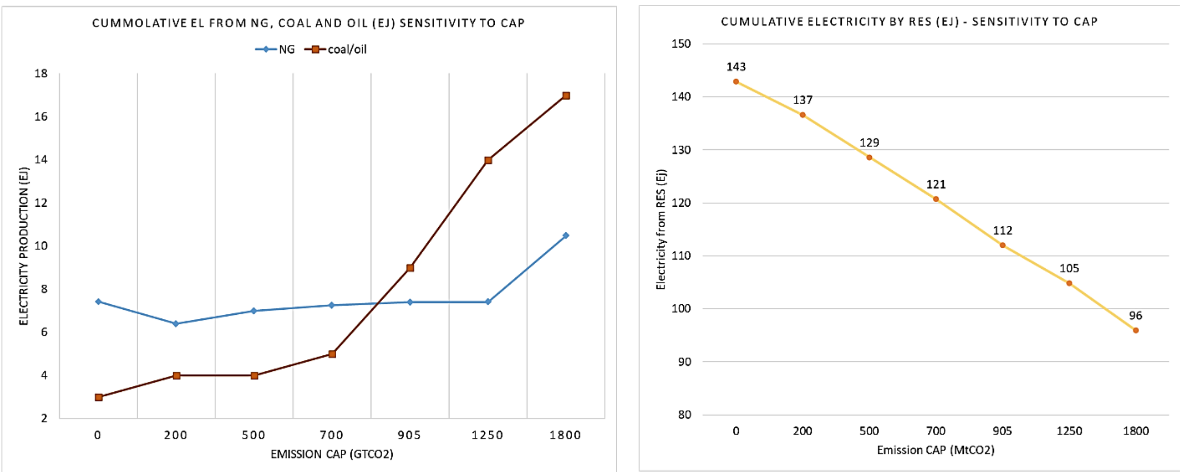

Figure 31. Electricity production by NG and coal/oil and RES and sensitivity to emission CAP

5.9.3. Sensitivity to Fuel price (NG, oil, coal)

Increasing fuel prices (oil, coal, and NG) leads to less participation of GT in the electricity production market, specifically, the application of GT using NG and NG+CCS. Lower fuel prices (half of the reference case) lead to higher electricity production by GT (4 EJ) combusting NG with CCS technology compared to current prices in the GET model (0 EJ using NG+CCS). In contrast, double fuel prices show the maximum value of electricity production using H2 (*Figure 32*). As could be expected, higher fuel price leads to less NG and more H2 participation as GT fuels. However, the relation between fossil fuel price and electricity production using H2 is not linear. *Figure 33* provides trends for electricity production using NG (as GT fuel), coal, and oil and their trend for different prices. While electricity from coal and oil has a decreasing trend, the share of NG is constant after fossil fuel prices increase by 1.5, and at the same time, from *Table 19*, RES share increases.

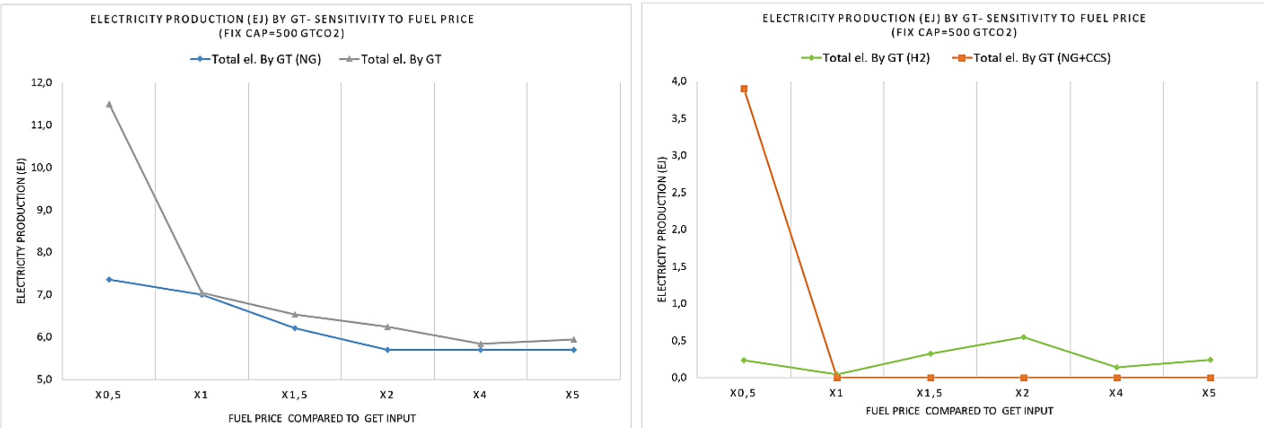

Figure 32. Electricity production (EJ) in different GT configurations and sensitivity to fuel price

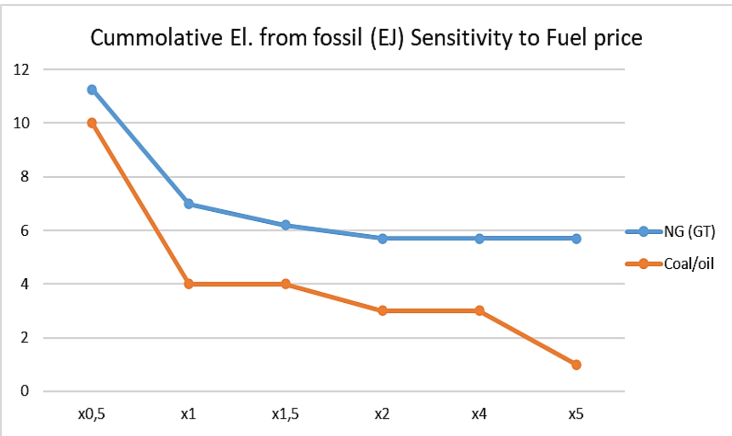

Figure 33. Electricity production (EJ) by NG and fossil fuels and sensitivity to fuel prices.

Table 19. Fossil fuel price compared to the reference case and electricity production by RES.

Fossil price	X0.5	X1	X1.5	X2	X4	X5
El. By RES (EJ)	122	129	130	132	137	146

5.9.4. Sensitivity to Hydrogen and RES CAPEX

In this section, a range of different CAPEX for converting RES and H2 to electricity has been applied to the reference case to check the sensitivity of results to these parameters. *Figure 34* demonstrates how the decreasing cost of hydrogen technology leads to a significant increase in the share of electricity production using H2-fueled GT plants. Electricity production using GT reached 36 EJ from the value of 6.9 EJ in the reference case, and electricity production share by GT using hydrogen reached 29 EJ from 0.04 EJ in the case of decreasing cost of H2 to electricity technology by 0.25 (x0.25) of reference case (x1).

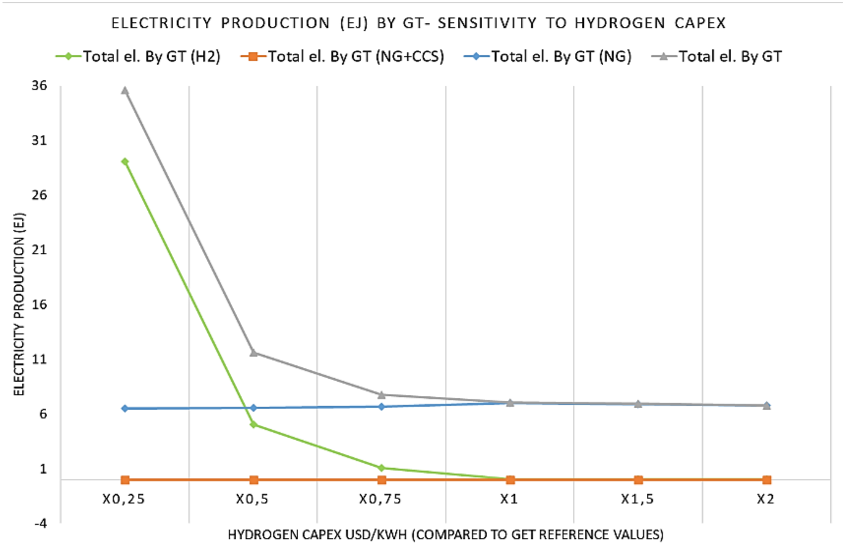

Figure 34. Electricity production (EJ) in different GT configurations and sensitivity to H2 CAPEX

On the other hand, different values of CAPEX for electricity generation with RES lead to very interesting results and confirm the results from similar scenarios in previous sections. As presented in *Figure 35*, two different trends could be under consideration for various ranges of RES penetration. Overall, electricity production by GT application has an increasing trend by using NG and CCS in case of more expensive RES technology (less technology penetration). On the other hand, electricity from H2 has higher values in the case of cheaper RES technology. Still, for very low CAPEX of one-fourth of the reference case (x 0.25) and higher CAPEX compared to the reference case, the H2 share is zero.

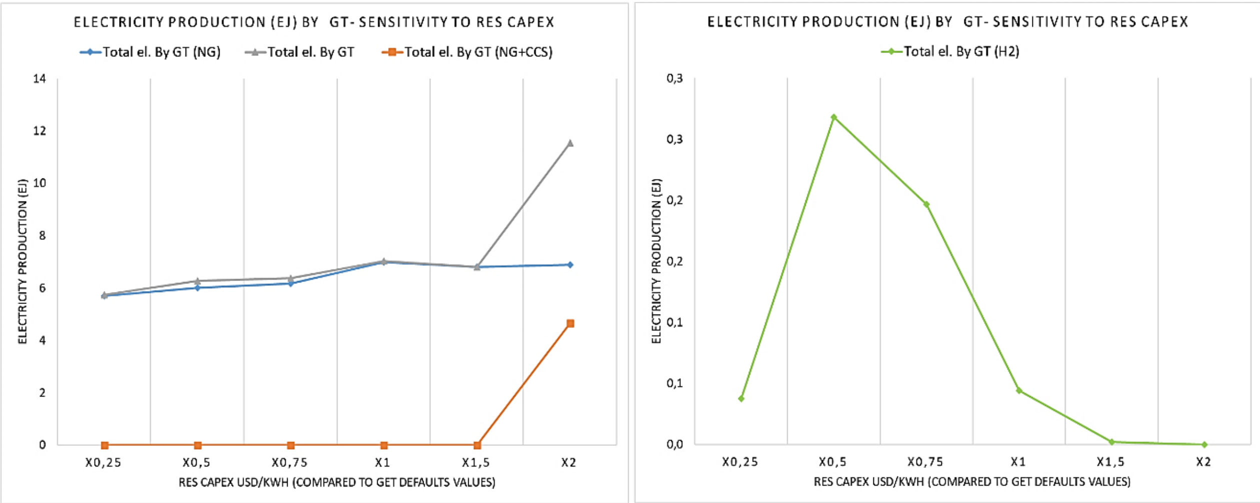

Figure 35. Electricity production (EJ) in different GT configurations and sensitivity to RES CAPEX

5.9.5. Carbon Storage Available Capacity

More available geological storage capacity for emissions is essential for carbon capture and storage solutions in the electricity market. The sensitivity analysis results in this section reveal the relation between storage capacity and GT application in modeling outputs. As illustrated in *Figure 36*, having less capacity for emission storage leads to more participation of gas turbines in electricity production, with a higher share using hydrogen fuels gas turbines and less share from NG. In the case of zero capacity, 8.29 EJ electricity is produced by GT plants compared to the reference case with 1,000,000 $MtCO_2$ capacity and 7 EJ electricity production. In addition, by decreasing storage capacity, the electricity production trend using NG (Not using CCS) is downward, and the electricity from the hydrogen-fueled GT trend is upward. An interesting result from this sensitivity analysis is the constant value of electricity production by GT (NG as fuel) for a capacity larger than 1,000,000 $MtCO_2$; also, electricity production using NG and CCS is zero for all different capacities. Hydrogen is an important source of electricity production for smaller capacity values by GT. In larger capacities, there is a considerable increase in electricity production by fossil fuels (oil and coal), as illustrated in *Figure 37*. At the same time, it is more optimal to use these fossil fuels with CCS technology and decrease the application of GT but with NG combustion without CCS since it has less pollution than cheaper but more carbon-intensive fossil fuels. Finally, besides model outputs, it is crucial to consider social acceptance, technical factors, and availability limits for using carbon storage capacities worldwide and in Europe.

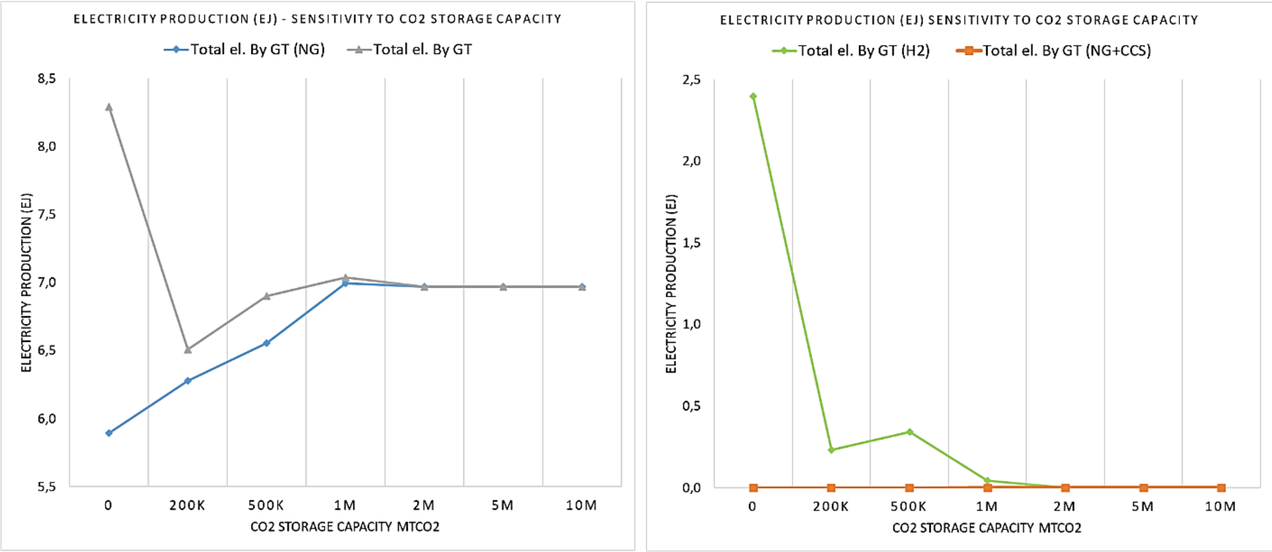

Figure 36. Electricity production (EJ) in different GT configurations, sensitivity to storage size

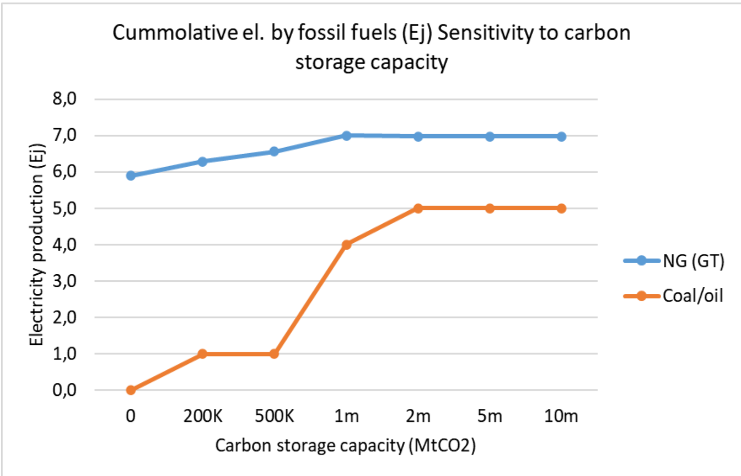

Figure 37. Electricity production (EJ) by NG and fossil fuels and sensitivity to CCS capacity

6. Discussion and Conclusion

A summary of all the modeling results for different scenarios and sensitivity analysis cases is presented in this section. Modeling results help evaluate the future share of gas turbines and related sustainable solutions in a more sustainable electricity market. This study focused on carbon capture and hydrogen fuel solutions for gas turbine power plants under the effect of EU ETS policies in a techno-economic context. As the main measures in EU ETS, policymakers could decide about total emission CAP, CO_2 cost, and target Net Zero year. Meanwhile, parameters such as phasing out old technologies or fuel prices and investment cost of renewable energies could be affected by limiting or supporting policies and different conditions in the market as well as technical developments. Some technical parameters, such as available geological storage capacities and power plant electrical efficiencies (see *Equation* 1), are also important inputs for modeling. As mentioned in the results section, GT power plants' combined cycle configuration has a dominant share of the future electricity market due to higher output efficiency.

As one of the key policies in EU ETS, results show that emission CAP has a significant effect on the future energy transition. Increasing CAP value (unfavorable for a sustainable future) led to higher electricity production by GT using NG as the primary fuel and higher production share using capturing technology compared to the reference case. The reason for increasing capturing in the GT plant, regardless of more available CAP, is more expansion of electricity by cheaper fossil fuels such as coal and oil. Applying higher carbon cost simultaneously with larger CAP leads to a significant increase in the share of capturing solutions for electricity production by GT. On the other hand, more limited CAP, compared to the reference scenario, leads to an overall decrease in electricity from GT plants, while adding carbon cost leads to more shares of CCS and H2. However, the total electricity by GT power plants increased slightly.

Regarding the carbon cost, as another valuable tool for decarbonization purposes, higher carbon cost leads to an increasing share of GT application for electricity production due to a decline in fossil fuel consumption; also, a share of capturing and H2 fuel in GT power plants expands more, regardless of emission CAP values. Although higher carbon costs, in combination with more limited CAP, lead to a considerable increase in the share of CCS and H2 in electricity production by GTs. In addition, combining higher carbon costs with more expensive fossil fuels (coal and oil) will increase GT application, including a considerable share of capturing technology for natural gas fuel.

An interesting part of the result about electricity from renewables (wind and solar) is a small share of electricity by hydrogen-fueled GT, with higher and lower investment costs of RES technologies. Electricity from RES typically is the most cost-effective power production method without converting renewables to hydrogen and later used in gas turbine combustion. However, in an energy system having large shares of RES, there is a need for energy storage, and hydrogen thus plays a key role, mainly when it can be efficiently used to produce electricity in GTs. The higher share of cheap RES energy then needs small values of GT for combusting hydrogen. The low participation of wind and solar also leads to an extremely low share of hydrogen when there is no cheap electricity from RES to produce hydrogen. However, the whole share of electricity from GT, including capturing technology, has a significant increase in the absence of solar and wind technologies.

On the other hand, as expected, having lower investment costs for hydrogen production without change in RES investment costs leads to a remarkably high share of hydrogen production by hydrogen as sustainable fuel for GT power plants. Carbon storage capacity is also one important item in this study, while more capacities lead to more capturing and lower capacities lead to less total GT share but more hydrogen to electricity by GTs. Although selecting a closer period, such as 2050 for global Net Zero years -in parallel with the same year for Europe- did not impact GT's share in the European electricity market, adding carbon cost will expand the share of CCS and hydrogen for the gas turbine power plants in Europe while the total share of GT has not a noticeable increase.

In conclusion, it is possible to highlight the effect of CAP and carbon cost as the primary measures from EU ETS and increasing share of electricity production using carbon capture and hydrogen by gas turbine power plants. However, making decisions for increasing CO_2 price and limiting CAP should be under some consideration, such as available methods for managing the capturing emissions and the welfare of industries and society, investors' motivations, and GT manufacturer participation.

For future research, studying the best combination of carbon cost and CAP to help a more sustainable electricity market is possible. In addition, methods besides carbon storage for managing the captured CO_2 emission should be considered for development. Finally, having RES as a parameter with a high impact on the future energy system, including GT power plants, there is a field for more study regarding the optimal balance between RES investment and its penetration in the electricity market in parallel with different shares of hydrogen technology in gas turbine power generation units as a carbon-free fuel and storage method for renewable energy sources.

Table 20 summarizes results based on different variable inputs and the final effect on gas turbine share in the future electricity market under the effect of EU ETS policies considering other important technical variables.

Table20. A summary of study results for GT share in future affected by EU ETS policies

Variable input (EU ETS policy or technical)	**GT electricity production share in different modes**			
	Overall GT share	**GT share with NG fuel without CCS**	**GT share with NG fuel with CCS**	**GT share with hydrogen fuel**
CAP (More limit)	Decreased	Decreased	Decreased	Increased
Carbon cost (Without CAP)	Decreased	Decreased	Increased	Increased
Limited CAP + Carbon cost	Increased	Decreased	Increased	Increased
Net Zero Year 2050 + C cost	Increased	Decreased	Increased	Increased
Higher fossil fuel price +C cost	Increased	Constant	Increased	Increased slightly
RES lower CAPEX	Decreased	Constant	Decreased	Decreased
Hydrogen lower CAPEX	Increased significantly	Constant	Constant	Increased significantly
Higher power-plant efficiency	Increased	Increased	Increased	Increased
Carbon storage higher capacity	Increased	Increased	Increased	Decreased

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Appendices

Appendix 01 - Modeling output data sets (in all results graphs file)

Appendix 02 - Electricity production technology mix in Europe

Appendix 03 – Atmospheric CO_2 concentration

Appendix 04 – Electricity generation emissions trends

Appendix 05– Trends for electricity production by GT with CC and H2 for all cases

Appendix 06– Cumulative electricity production by RES and Fossil fuels for different cases

Appendix 01 - Modeling output data sets (in all results graphs file)

Model output data that are related to future energy transition in Europe are listed as the following, although the same data sets are available for other regions and as global values:

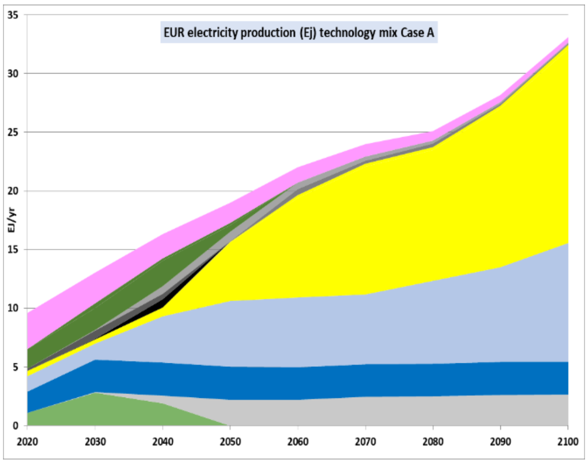
- CO_2 concentration (ppm) in atmosphere
- CO_2 marginal price
- CO_2 emission in Europe (Total, electricity sector)
- Electricity production technology mix
- Hydrogen application for different purposes in Europe
- Hydrogen production by source of energy
- Carbon captured in different sectors ($MtCO_2$)
- Carbon stored in different sectors ($MtCO_2$)
- Total energy supply by primary sources
- Different energy source applications (conversion) include Bio, NG, oil, and coal.
- Different energy sources demand
- Transport energy sources mix

There are other outputs from the modeling progress for each scenario, which are part of the overall calculation in the model but are not related or useful in the scope of this study, and there is no need to mention them in this section.

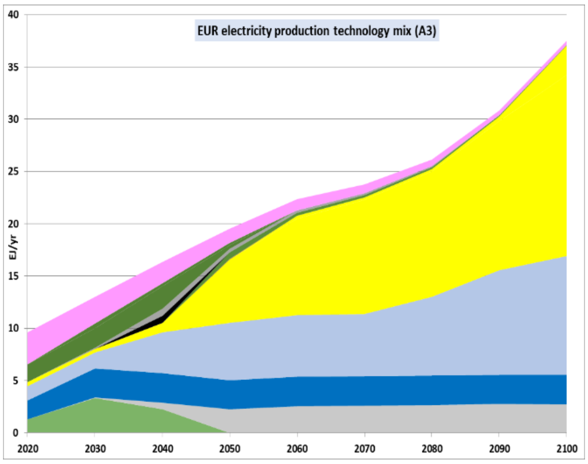
Appendix 02 - Electricity production technology mix in Europe

Here, electricity production (EJ) technology mixes for more important scenarios presented:

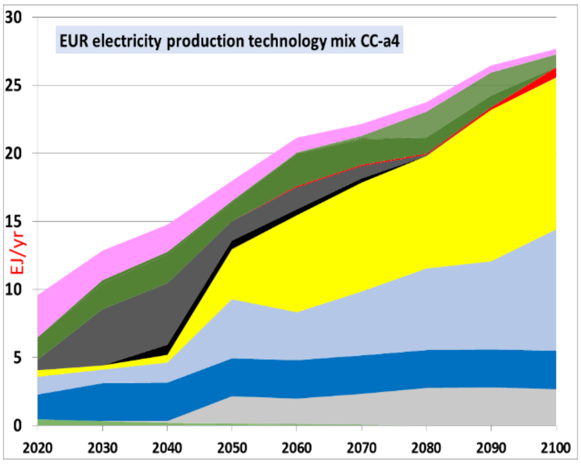
A, GET default inputs.



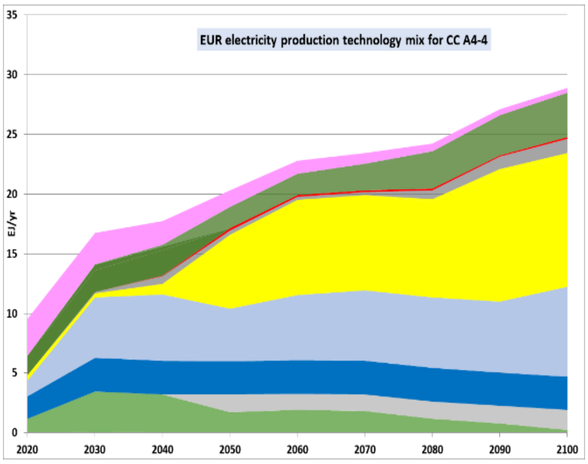
SC-A3 reference case for simple cycle



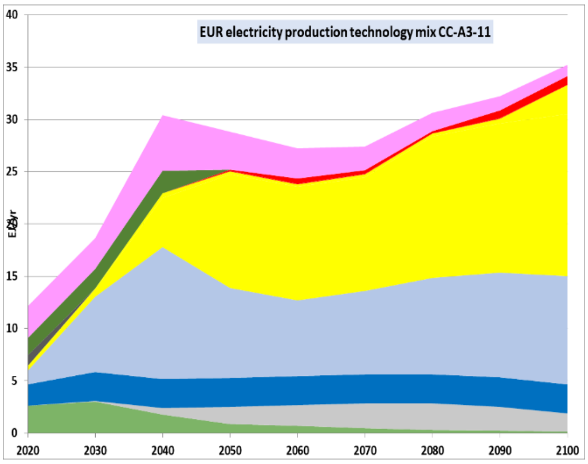
CC-A4, Larger CAP of 1,700,000 $MtCO_2$



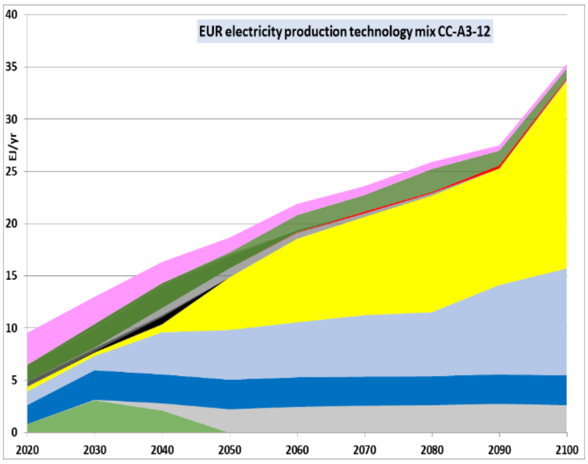
CC-A4-4, Larger CAP, and carbon cost of 200 USD/tCO_2



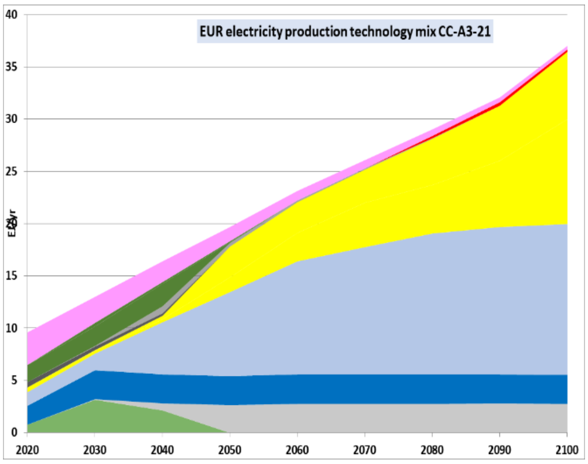
CC-A3-11, Carbon storage capacity of 0 $MtCO_2$



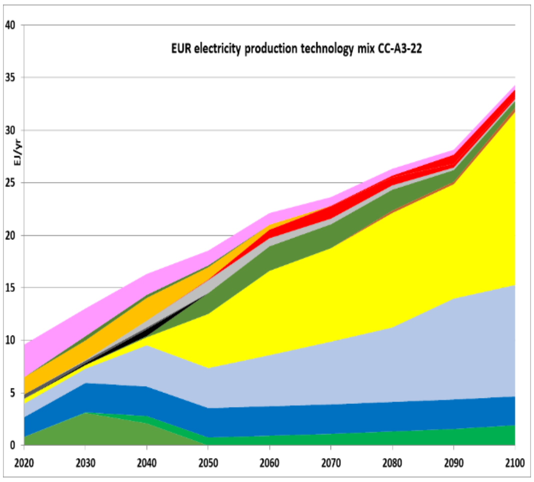
CC-A3-12, Carbon storage capacity of 5,000,000 $MtCO_2$



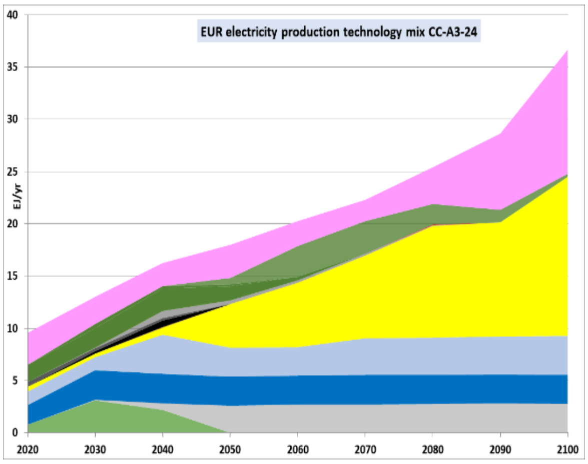
CC-A3-21, More RES penetration compared to the reference case.



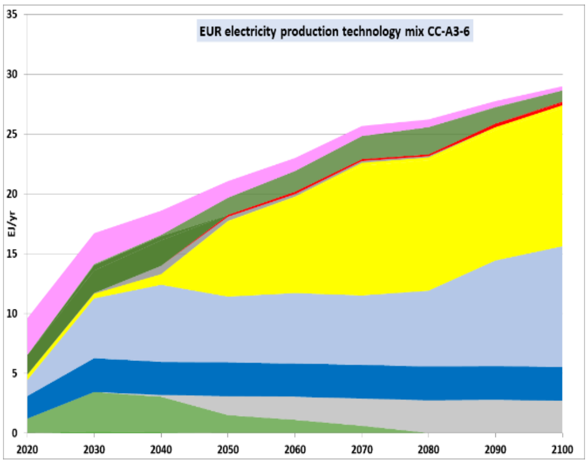
CC-A3-22, More H2 penetration compared to the reference case.



CC-A3-24, Less RES penetration compared to the reference case.



CC-A3-6, carbon cost of 200USD/tCO_2+ expensive fossil fuels

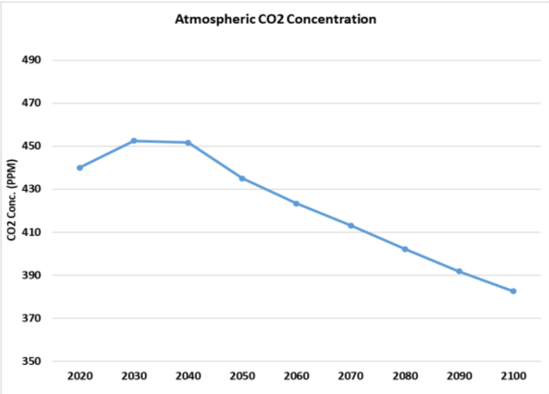


EUR MOX 0	EUR FBF 0	EUR EU1 0	EUR EU4 0	EUR CH4 cg_dec	EUR CH4 dec	EUR CH4 cg
EUR CH4 0	EUR pellets dec	EUR H2 cg	EUR H2 0	EUR coal cg_dec	EUR coal dec	EUR coal cg
EUR coal 0	EUR oil cg_dec	EUR oil dec	EUR oil cg	EUR oil 0	EUR solar cg	EUR solar 0
EUR wind 0	EUR hydro 0	EUR bio cg_dec	EUR bio dec	EUR bio cg	EUR bio 0	

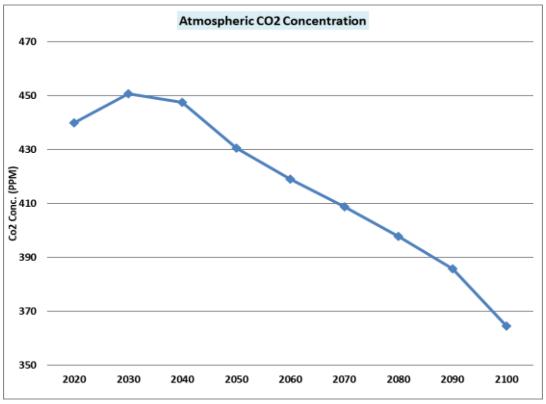
Appendix 03 – Atmospheric CO_2 concentration

Here, graphs for global atmospheric CO_2 concentration for more important scenarios have been presented:

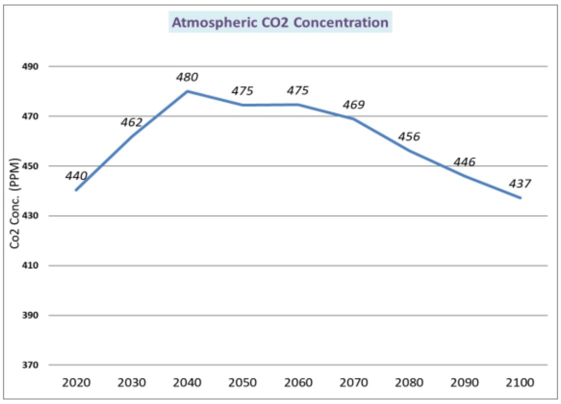
A, GET default inputs.



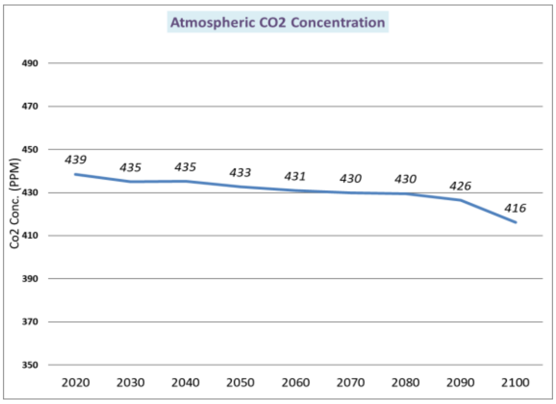
SC-A3 reference case for simple cycle



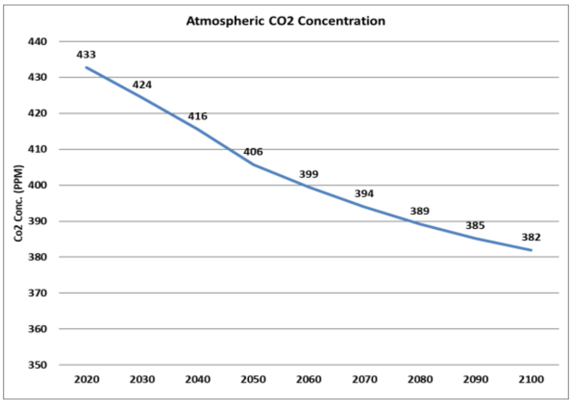
CC-A4, Larger CAP of 1,700,000 $MtCO_2$



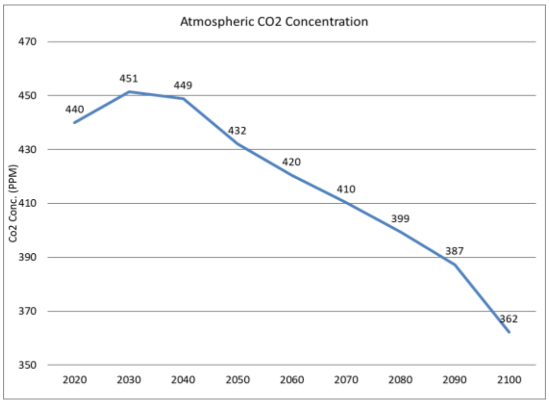
CC-A4-4, Larger CAP, and carbon cost of 200 USD/$tCCO_2$



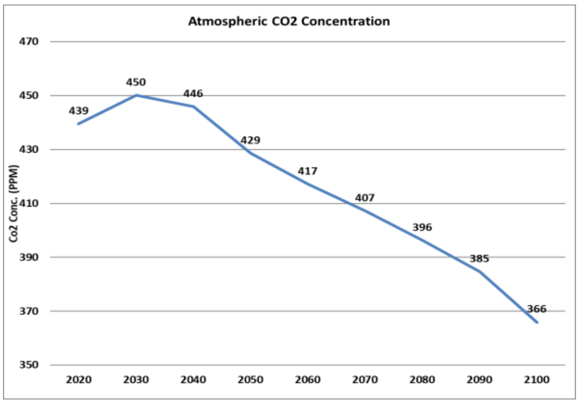
CC-A3-11, Carbon storage capacity of 0 Mt O_2



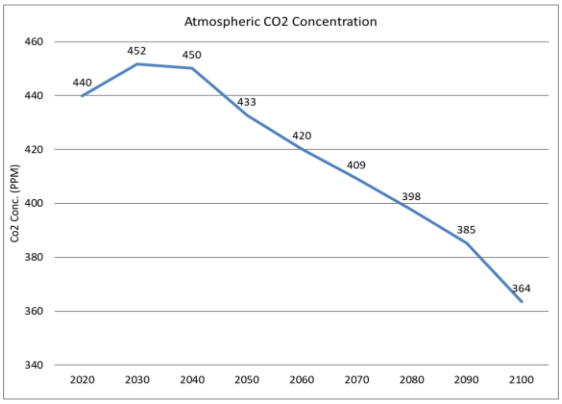
CC-A3-12, Carbon storage capacity of 5,000,000 $MtCO_2$



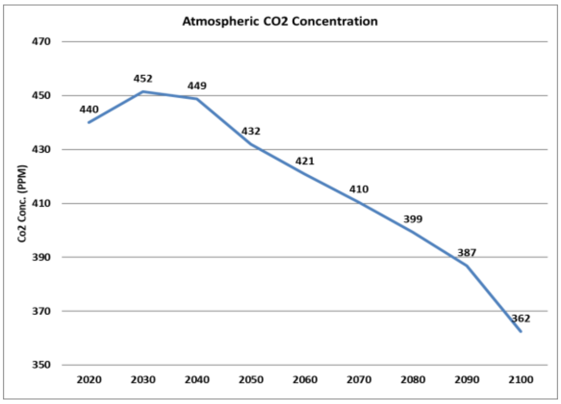
CC-A3-21, More RES penetration compared to the reference case.



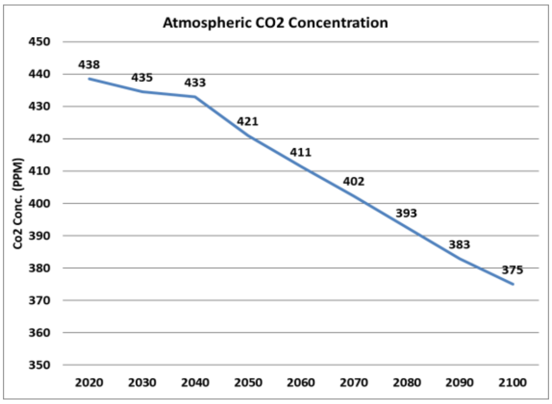
CC-A3-22, More H2 penetration compared to the reference case.



CC-A3-24, Less RES penetration compared to the reference case.



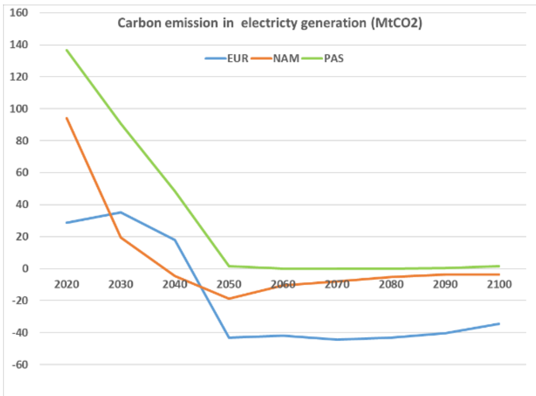
CC-A3-6, carbon cost of 200USD/tCO_2 + expensive fossil fuels



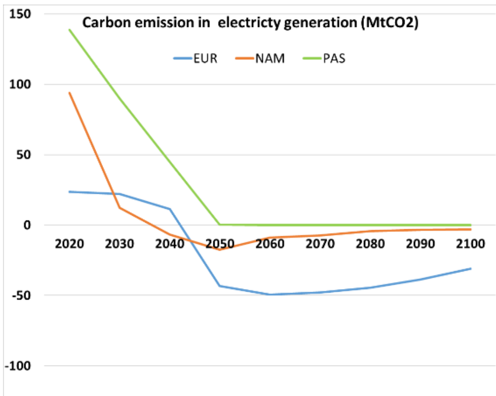
Appendix 04 – Electricity generation emission trends

Here, graphs for emission from electricity production for more important scenarios in Europe has been presented:

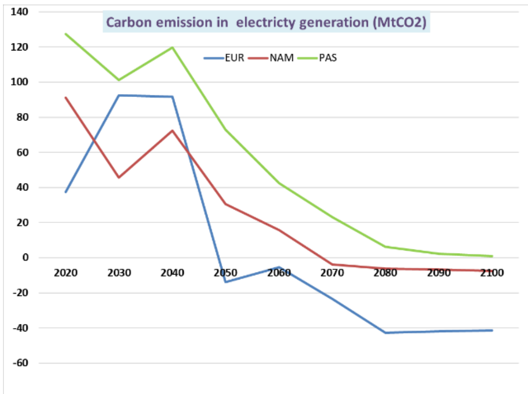
A, GET default inputs.



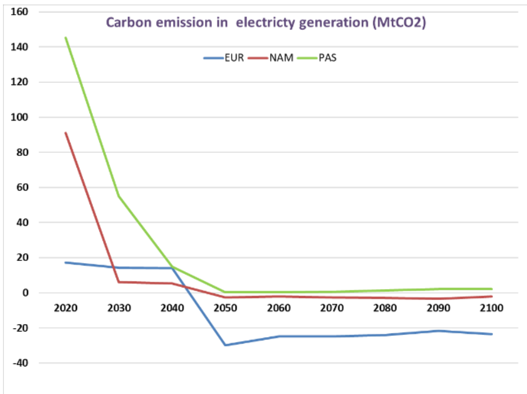
SC-A3 reference case for simple cycle



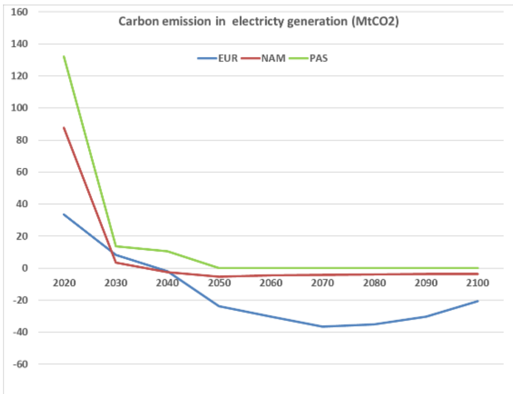
CC-A4, Larger CAP of 1,700,000 $MtCO_2$



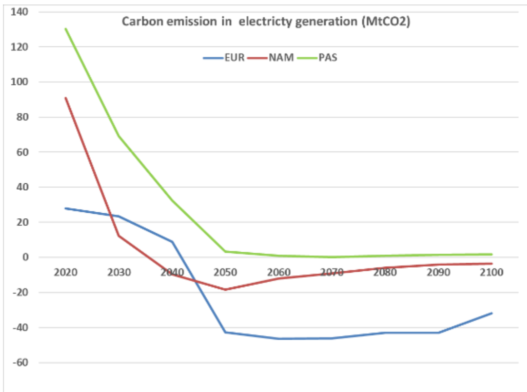
CC-A4-4, Larger CAP, and carbon cost of 200 USD/tCO_2



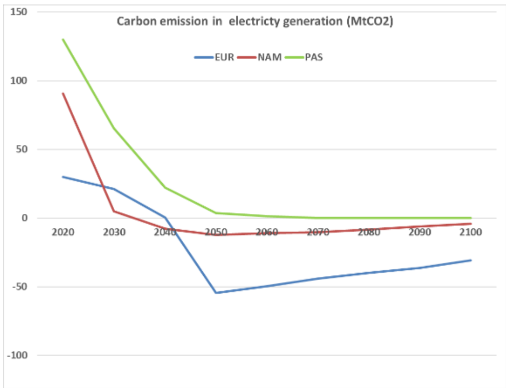
CC-A3-11, Carbon storage capacity of 0 $MtCO_2$



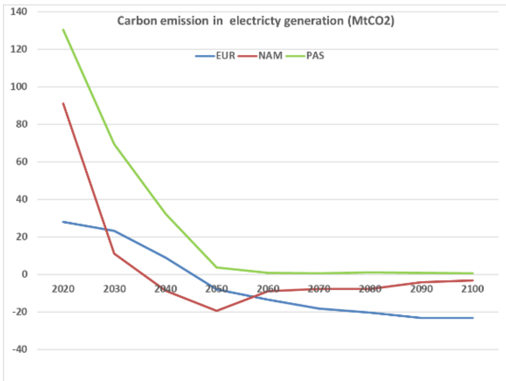
CC-A3-12, Carbon storage capacity of 5,000,000 $MtCO_2$



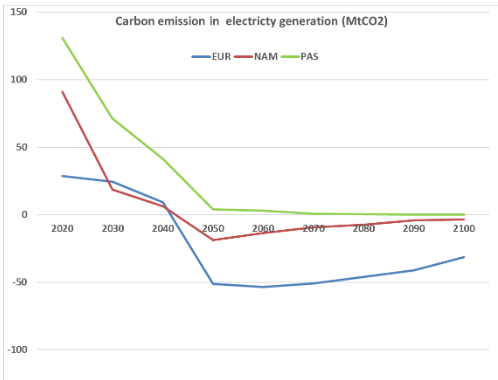
CC-A3-21, More RES penetration compared to the reference case.



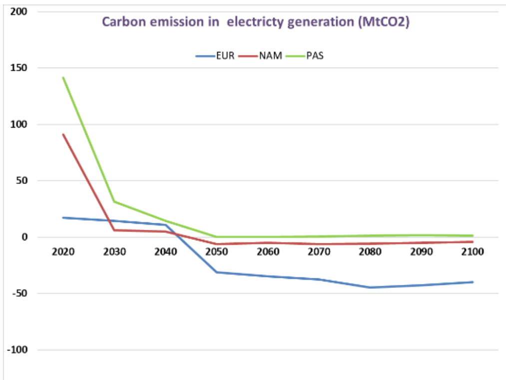
CC-A3-22, More H2 penetration compared to the reference case.



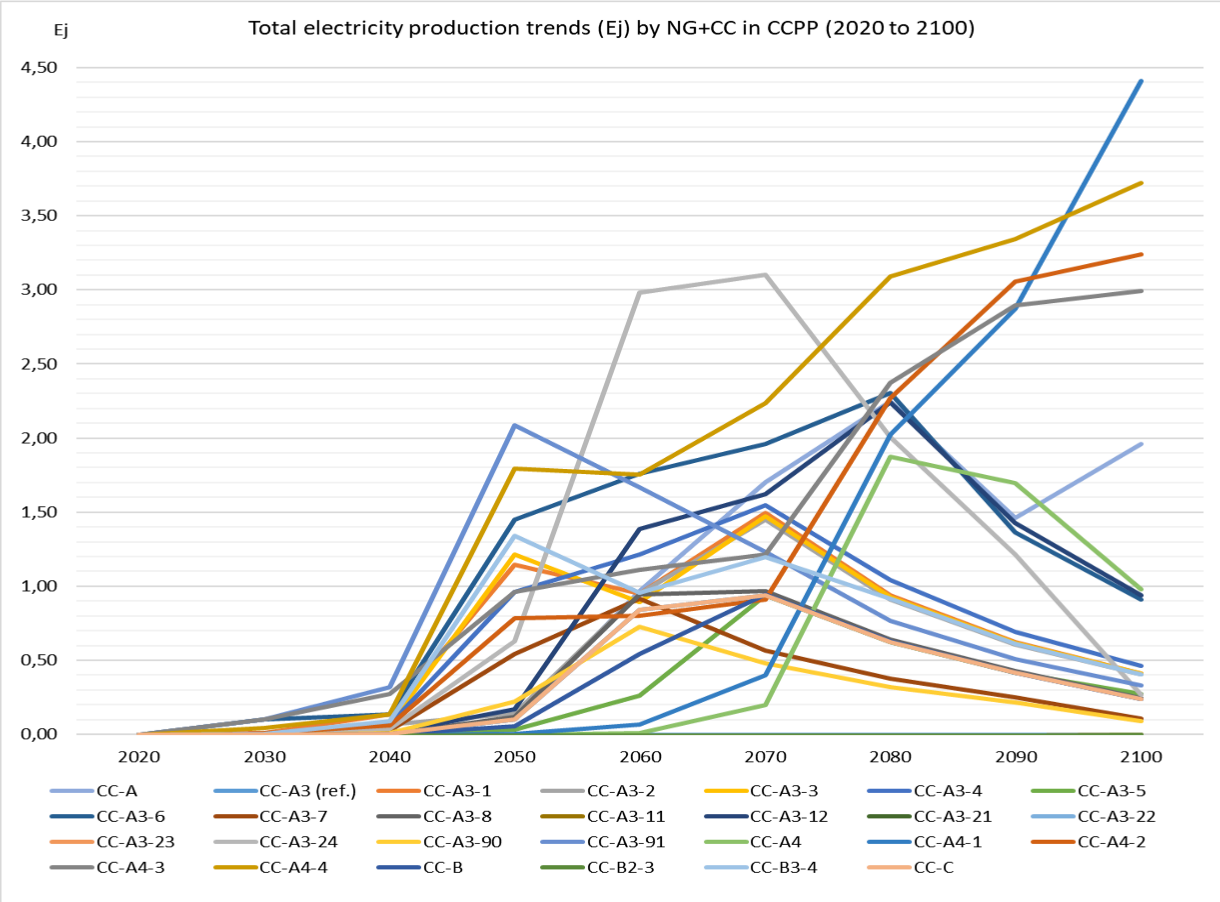
CC-A3-24, Less RES penetration compared to the reference case.

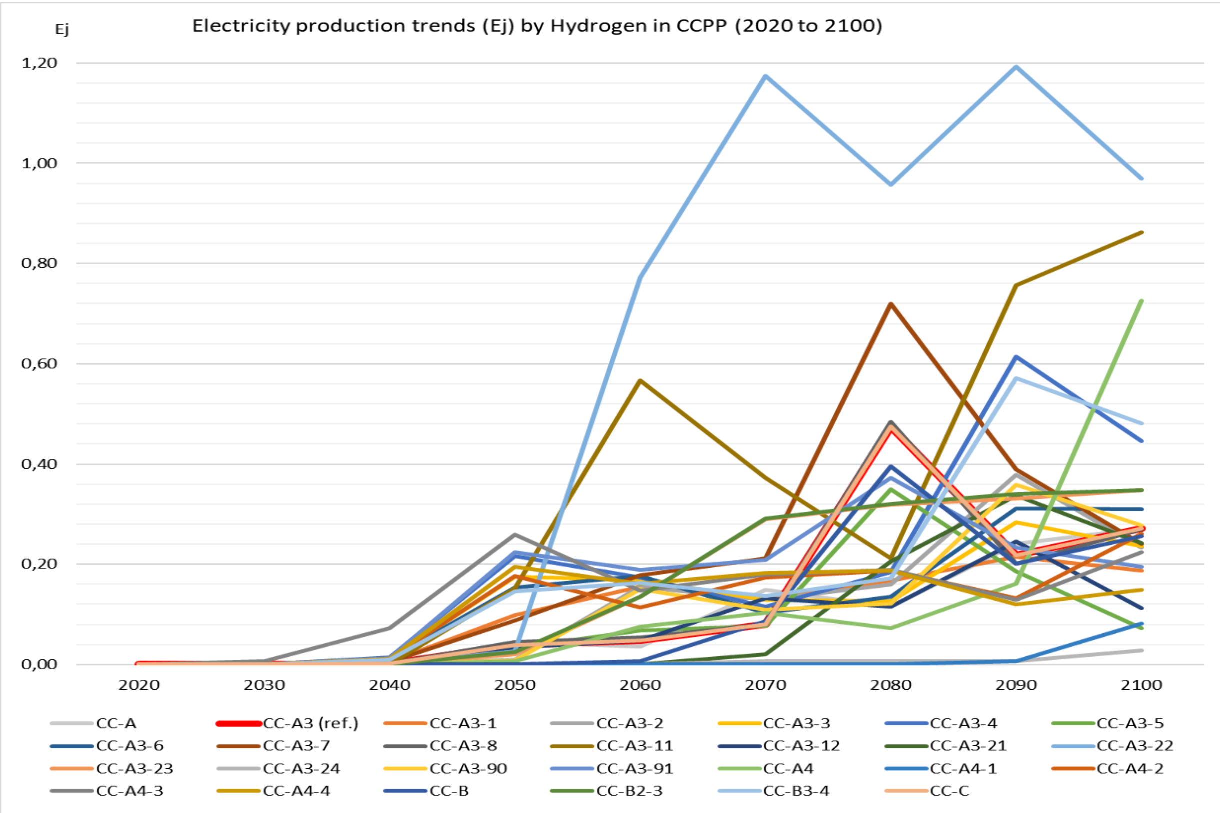


CC-A3-6, carbon cost of 200USD/tCO_2 + expensive fossil fuels

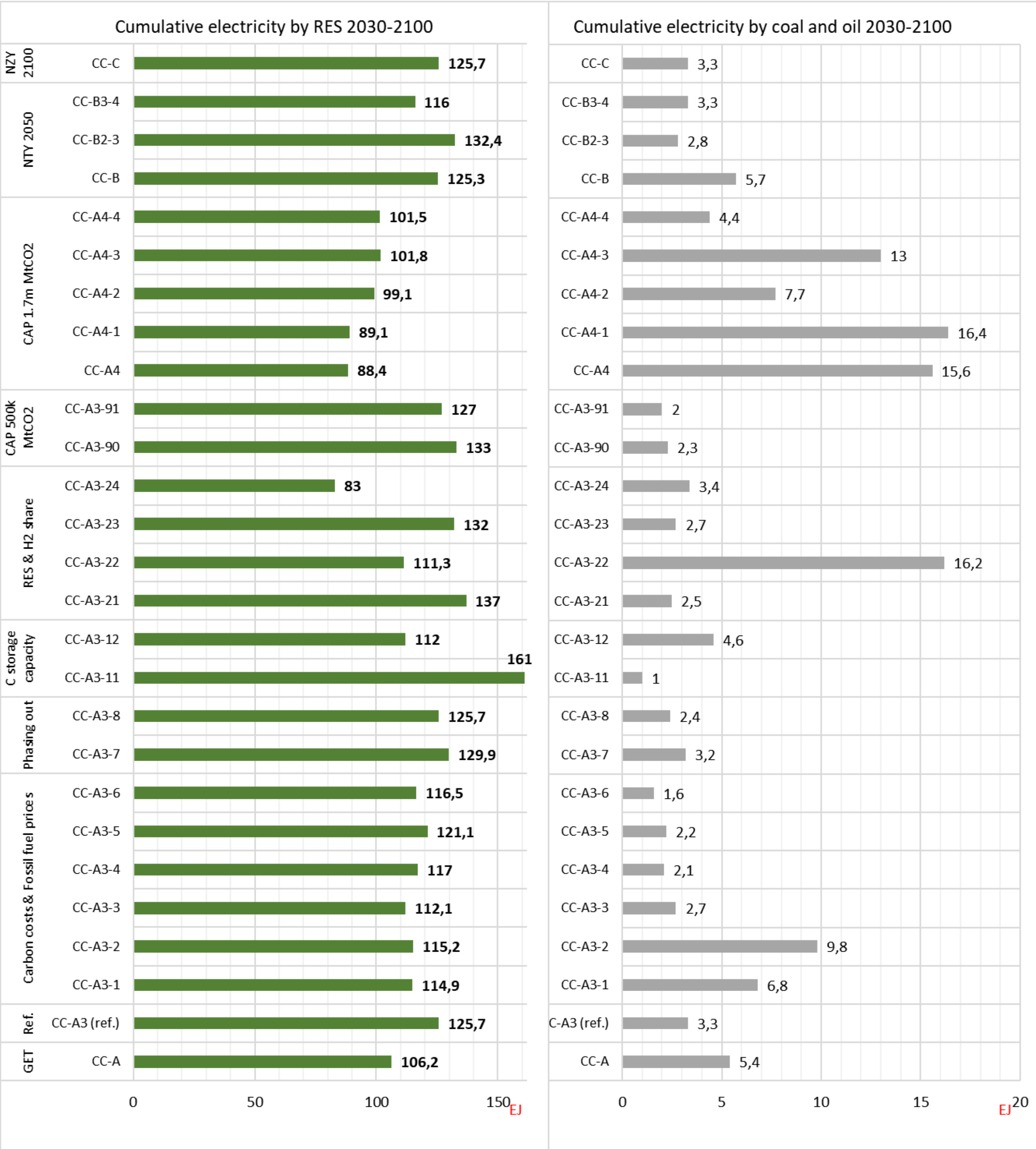


Appendix 05 – Trends for electricity production by GT with CC and H2 for all cases





Appendix 06 – Cumulative electricity production by RES and Fossil fuels for different cases



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