Net Zero Transformation Strategies for Fossil fuel Power Plants

Tso, Chunto / Vice President, Taiwan Institute of Economic Research

Chen, Yen-haw / Director, Research Division I, Taiwan Institute of Economic Research

Yu, Ching-yun / Deputy Director, Research Division I, Taiwan Institute of Economic Research

Chen, Ying-jung / Assistant Researcher and Deputy Chief, Research Division I, Taiwan Institute of Economic Research

Zheng, Yun-sheng / Assistant Researcher, Research Division I, Taiwan Institute of Economic Research

Abstract

The International Energy Agency (IEA) recommends phasing out all unabated power plants by 2040. Fossil fuel power plants account for 70.1% of the total installed generation capacities in Taiwan. Carbon capture, utilization and storage (CCUS) is an effective means to achieve net-zero transformation of the power sector by improving the performance of existing power generation plants and expanding the production of low-carbon hydrogen. The estimate of this study shows that CCUS may make a significant contribution to net zero emissions (NZE) of the power sector in Taiwan; besides, a mechanism titled Carbon-Free Energy Certificate (C-FEC) mechanism may convert the greenhouse gas (GHG) reductions outside the value chain of power plants into GHG reductions within the value chain. Along the way to NZE, the following policies and actions need to be adopted to facilitate CCUS related markets: fiscal measures, sharing CO_2 transmission and storage infrastructure among industries, and get together domestic and foreign enterprises to realize industrial transformation/upgrading.

Key Words: Net Zero Emissions; Carbon Capture, Utilization and Storage; Negative Emission Technologies; Carbon Dioxide Removal; Levelized Cost of Electricity; Carbon-Free Energy Certificate (C-FEC).

I. Introduction

To curb the worsening of climate change, many countries are actively drafting emissions reduction targets. In particular, numerous countries are striving to achieve "net zero emissions" in order to realize the Paris Agreement's target of preventing the global temperature from rising more than 1.5°C. According to analysis by IEA, power generation would be of the utmost importance during the net zero transition. In order to quickly reduce CO_2 emissions within the next 30 years, compared with current methods, we will need to make much more extensive use of policy methods and technologies. The chief methods supporting the decarbonization of energy systems worldwide include energy efficiency, changes in behavior, electrification, renewable energy, hydrogen energy and hydrogen-based fuels, bioenergy, and carbon capture, utilization and storage (CCUS).

Taiwan has installed generating capacity of 60,332 MW, and thermal generating units account for 42,302 MW of this, or 70.1% of total installed capacity, of which 26,341 MW is from the Taiwan Power Co. (Taipower), 8,753 MW from private power plants, and 7,207 MW from self-owned generating equipment. At present, Taiwan has 7 generating units that have been in operation for more than 30 years, 18 units for 21-30 years, and 18 units for 20 years or less. According to IEA's roadmap, coal-fired power plants with unabated emissions should be shut down by 2040. Accordingly, apart from adopting renewable energy on a large-scale, if Taiwan wishes to develop a decarbonized energy system, it must adopt carbon capture and storage technology as one of the countermeasures for transition to net zero.

This paper introduces CCUS technology and the impact of a net zero transition on the development of the energy and power sector, analyzes the state of carbon emissions and adoption of carbon capture technology at thermal power plants of Taiwan power company (Taipower), and provides recommendations concerning how net zero power plants can assist enterprises in making a net zero transition in Taiwan.

II. Introduction to the net zero transition and negative emission technologies

According to a report issued by the UN Intergovernmental Panel on Climate

Change (IPCC), in contrast to carbon emissions, negative emissions technologies (NETs) involve the removal of CO_2 from the atmosphere (Carbon Dioxide Removal, CDR) and can assist in keeping the increase in the earth's temperature from exceeding 1.5°C. Most current pathways for meeting the targets of the Paris Agreement will require the large-scale deployment of NETs during the second half of this century. According to IPCC's calculations, approximately 12 billion tons of CO_2 must be captured and stored annually after 2050, which is equivalent to one-third of the world's current annual emissions.

NETs mainly include CCUS for production process, CDR from the atmosphere or relevant treatment, and carbon sinks involving the absorption and storage of carbon by environmental systems.

I. CCUS for production process

In its 2020 report on the energy technology outlook, IEA asserted that CCUS will be one of the key technologies helping the world achieve net zero. The development of net zero energy systems will require profound changes to the methods by which energy is produced and used, which can only be achieved through the use of a series of far-reaching appropriate technologies. Apart from electrification, hydrogen energy, and sustainable bioenergy, CCUS will play an important role. This technology is the only means of directly reducing and eliminating the CO_2 emissions of key sectors, and balancing out unavoidable emissions, which is a key goal of net zero emissions. IEA has also pointed out that CCUS will contribute to a clean energy transition via the following advantages [1]:

(I) Solving the emission problems of existing energy infrastructure: CCUS can modify and improve existing power plants and factories in terms of emissions. If modification measures are not taken, existing power plants and factories worldwide may emit as much as 600 billion tons of CO_2 during the coming 50 years, and this amount is equivalent to approximately 17 times of current global emissions.

(II) Solving several of the most challenging emission problems: Heavy industry currently accounts for nearly 20% of global CO_2 emissions. CCUS technology is the only method that can greatly reduce CO_2 emissions from cement production. In many

places, CCUS is the most economical and effective means of reducing emissions from the production of steel and chemical products. The captured CO_2 can serve as a key part of a synthetic fuel supply chain using CO_2 and hydrogen. The resulting synthetic fuel is one of the few low-carbon options for long-distance transportation (particularly air transportation).

(III) Producing economically-efficient low-carbon hydrogen: CCUS can support the rapid expansion of low-carbon hydrogen production, which will meet future demand and the current needs of new applications in the transportation, industry, and construction sectors.

(IV) Removing carbon from the atmosphere: In the case of CO_2 emissions that cannot be avoided or directly reduced, CCUS will be an important technological basis for eliminating carbon emissions and developing net zero energy systems.

II. Direct carbon removal (CDR) from the atmosphere or relevant treatment

CDR refers to removal of CO_2 directly from the atmosphere. As opposed to carbon emissions, CDR methods or technologies are typically described as negative emissions. The removed gases are not limited to CO_2, but also include such other greenhouse gases as methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). This can be more broadly referred to as greenhouse gas removal. CDR methods include natural solutions, enhanced natural processes, and technological solutions. Solutions based on natural processes include afforestation (planting trees on previously unforested land) and reforestation (re-establishing forests on land that had previously been forested). Enhanced natural processes include land management methods that increase land utilization; Modern agricultural methods (such as the use of biochar or finely-ground mineral silicate rock) can be used to increase the carbon content of the soil, and ocean fertilization can be used to increase the ability of the ocean to absorb CO_2 through the addition of nutrients (Table 1).

Table 1 Major carbon removal methods and technologies

Method	Type of application	Current stage of development	Carbon removal potential ($GtCO_2$)*	Cost of CO_2 capture (USD/tCO_2)
Bioenergy with carbon capture and storage (BECCS)	Technology	Demonstration	100-1,170	15-85
Direct air carbon capture and storage (DACCS)	Technology	Demonstration	108-1,000	135-345
Enhanced mineral weathering	Enhanced natural processes	Basic research	100-367	50-200
Land management and biochar production	Enhanced natural processes	Early adoption	78-1,468	30-120
Ocean fertilization/alkalinization	Enhanced natural processes	Basic research	55-1,027	-
Afforestation/reforestation	Natural methods	Early adoption**	80-260	5-50

Notes: *Cumulative carbon removal potential to 2100. Estimates of carbon removal potential are not included.

**Although afforestation or reforestation is an existing method, it is still at the early adoption phase as regards the actual removal of carbon.

Source: IEA (2020)

Current CDR methods consist of two types: One is the enhanced removal of carbon from the atmosphere employing existing natural processes, such as through increasing the absorption of carbon by trees, the soil, or other carbon sinks; The other involves the use of chemical processes, such as the direct capture of CO_2 from the atmosphere and storage in underground strata. There are great differences in the current stages of development for the various CDR methods; some are already mature agricultural or industrial technologies, while others are still mostly at the conceptual stage, and have not been verified or tested on a large scale. Several existing CDR methods have different negative carbon emissions potentials, and their cost and impacts also differ. IEA's descriptions of carbon removal methods reveal their potential roles and policy benefits:

(I) Carbon removal technologies can potentially offset the residual emissions of industries that cannot easily reduce their emissions, and can

therefore enable the energy industry as a whole to achieve net zero.

(II) From at least the end of the 20th century, carbon removal has commonly been seen as a means of achieving net negative emissions in the industrial sector, and can offset excess emissions during the early period when the greenhouse effect was taken less seriously. However, IEA also reminds us not to take carbon removal technology as a substitute for reductions in current emissions or as a reason for delaying other relevant actions.

(III) From a policy perspective, carbon removal technology is a hedging method, and can offset or alleviate the risk of delay or failure in the development and deployment of other CO_2 emissions reduction technologies. The development and deployment of new technologies is seldom a linear process, and unforeseen delaying factors may inevitably occur.

Direct air carbon capture and storage (DACCS) and bioenergy with carbon capture and storage (BECCS) are currently the main technological solutions to the problem of carbon removal, and are the two pathways potentially able to make the largest contributions to carbon removal as the energy sector seeks to achieve net zero emissions [2]. DACCS technology captures CO_2 directly from the atmosphere and transfers it to permanent storage; or provides it for uses such as food processing or the production of synthetic hydrogen fuel. However, these pathways will ultimately release CO_2. BECCS involves the conversion of biomass to energy, or the capture and permanent storage of CO_2 during the production of materials. Current examples include biomass power plants, plants producing pulp for papermaking, kilns used for cement production, and biofuel plants.

III. Impact of the net zero transition on the development of the energy and power sector

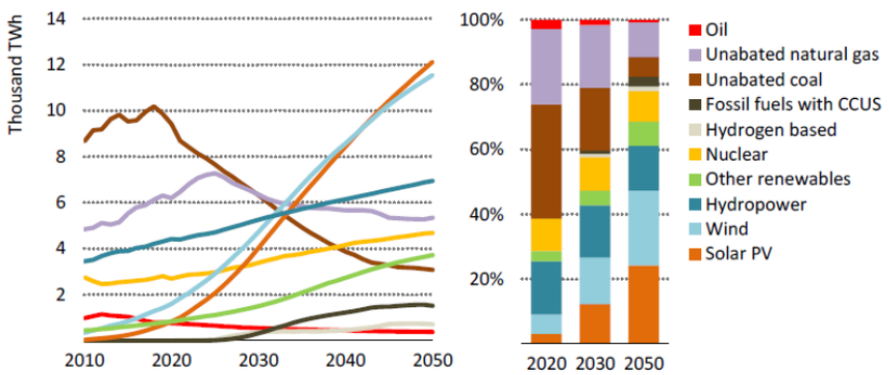
According to analysis by IEA, the power sector must undergo the greatest transformation during the net zero transition. The energy sector possesses many capital-intensive assets with long service lives, such as urban infrastructure, pipelines, refineries, coal-fired power plants, heavy industrial facilities, buildings, and large hydropower plants; the technological and economic service

life of these assets can commonly exceed 50 years. The greenhouse gas emissions of existing power sector assets worldwide account for approximately 50% of all global emissions, of which roughly 40% come from coal-fired power plants. If this energy infrastructure operates in the usual way, cumulative emissions from 2020 to 2050 will be over 650 billion tons, which exceeds the carbon budget needed to keep the earth's temperature from rising over 1.5°C by 30%. The cost of renewable energy power generation continues to decline, making power development more advantageous from 2020 to 2050. Since overall demand for power is projected to increase by 80%, the share of ultimate energy consumption attributable to renewable energy is expected to increase rapidly. However, in spite of the rapid growth of renewable energy, coal-fired power will continue to play a certain role in the generating mix for continuing economic growth, while facing geopolitical risks, or for economies not using nuclear energy.

According to IEA's analysis of the development of net zero pledges worldwide, global generating capacity will increase from 26.8 million GW in 2020 to 50 million GW in 2050, and the increase will be derived completely from low-pollution energy. Renewable energy will drive the future development of energy supplies, and renewable energy's share of the overall energy supply mix will increase from 12% in 2020 to 35% in 2050. Of this increase, 50% of renewable energy growth will come from solar and wind power, and another 30% will be derived from bioenergy with CCUS. If nuclear energy accounts for an unchanging share of the overall energy mix, the world will quickly decrease use of coal-fired power by 50% by 2050; this decrease will be chiefly due to the modification, updating, or decommissioning of coal-fired power plants. During the next 10 to 15 years, the developed economies will gradually retire their unabated coal-fired power plants. Fig. 1 shows that after the maximized development of renewable energy it will account for a 70% share of total power in 2050 under the generating mix called for by net zero transition pledges.

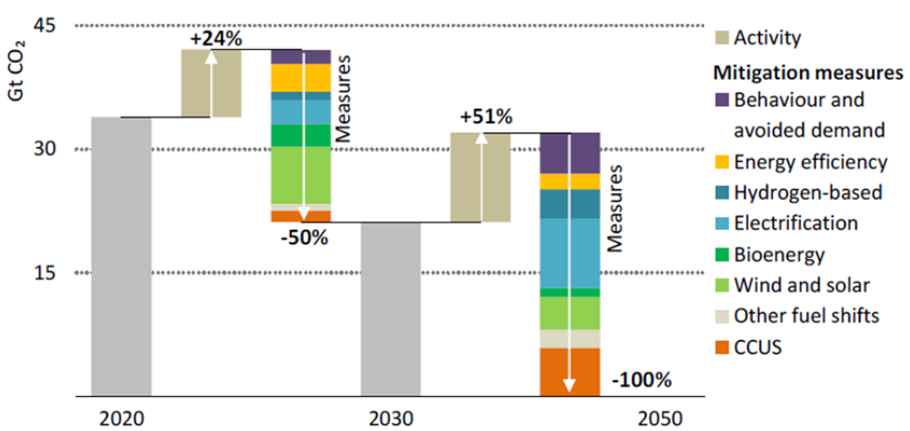
According to IEA's analysis, in order to quickly reduce CO_2 emissions during the next 30 years, in addition to existing methods, we will also need comprehensive policy approaches and technologies. The chief methods supporting the decarbonization of global energy systems

include energy efficiency, changes in behavior, electrification, renewable energy, hydrogen energy and hydrogen-based fuels, and bioenergy with carbon capture, utilization and storage (CCUS). Solar power, wind power, and energy efficiency will contribute one-half of the reduction by 2030, and the contribution of electrification, CCUS, and hydrogen energy will increase after that time (Fig. 2).



Source: IEA

Figure 1 2050 power generating mix under a global net zero transition pledge



Source: IEA

Figure 2 2020-2050 net zero mitigation and reduction measures

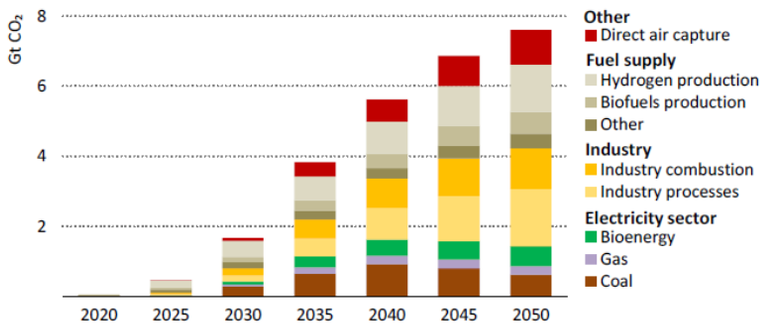
IV. Carbon capture, utilization, and storage (CCUS) and the net zero transition

CCUS will be one of the most effective ways for the power sector to deal with its greenhouse gas emissions during the net zero transition. CCUS can not only deal with emissions from existing assets, but also provide a cost-effective hydrogen production method enabling the rapid expansion of low-carbon hydrogen energy production. BECCS and DACCS technology can be used to achieve the removal of CO_2 from the atmosphere.

In the net zero transition, various policy measures will be required to establish markets promoting CCUS investment, and encouraging hydrogen energy and biofuel production, industry hub operations, and the upgrading of existing coal-fired power plants and other joint-use CO_2 transport and storage infrastructure. During the next 5 years, the scale of carbon capture by existing projects will increase slight from the current 40 million tons of CO_2. The scale of carbon capture will quickly increase during the subsequent 25 years due to the results of policy actions. IEA projects that 1.6 billion tons of CO_2 will be captured globally each year by 2030, and this figure will gradually increase to 7.6 billion tons annually by 2050. It is expected that 95% of the captured CO_2 will be permanently sequestered in rock strata, and the remaining 5% will be used to produce synthetic fuel. According to survey results, the potential CO_2 storage capacity of rock strata worldwide is far greater than needed to store the projected amount of CO_2 captured during the next few decades. By 2050, direct air carbon capture and bioenergy and carbon capture are expected to capture a total of 2.4 billion tons of CO_2 from the atmosphere, of which 1.9 tons of CO_2 will be permanently sequestered, and 500 million tons will be used in the production of synthetic fuel, which will be especially needed for air transportation [3].

By 2050, the power sector will account for 20% of all CO_2 capture (approximately 45% of this contribution will be from coal-fired power plants, 40% from bioenergy power plants, and 15% from gas-fired power plants). By 2050, the generating capacity of power plants equipped with CCUS will account for 3% of overall generating capacity, but the amount of CO_2 captured by these power plants will be relatively large. Because emerging and developing economies are continuing to build large coal-fired power

plants, the overhaul and upgrading of these power plants will play a fairly important role if CO_2 storage potential is available near plant site. In the case of the developed economies, equipping gas-fired power plants with CCUS will be even more important. In areas with low natural gas costs, such plants can provide low-cost dispatchable power to existing power grids (Fig. 3).



Source: IEA

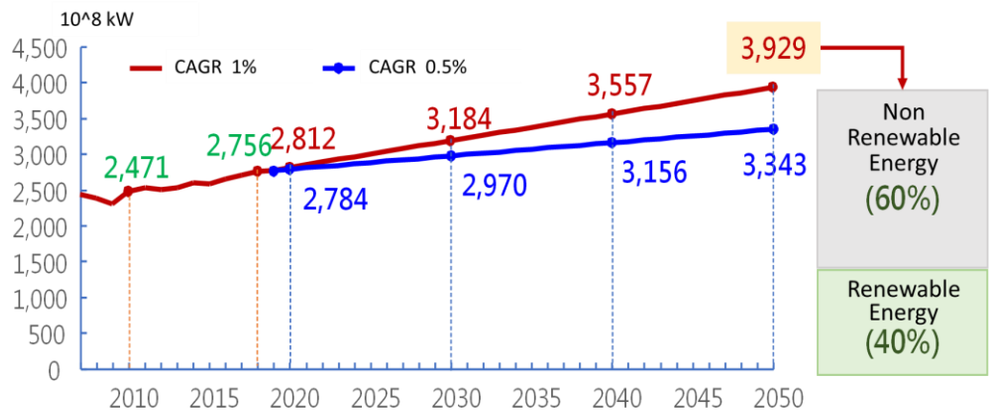
Figure 3 Global CO_2 carbon capture attributable to different sources following the net zero transition

V. Current state of fossil fuels and challenges facing net zero

If we assume that the average annual growth rate of power demand in Taiwan remains in the range of 0.5%-1% (2010-2020 period), then the total generating capacity will increase steadily from 27.56 TW in 2018 to 33.43-39.29 TW in 2050 (Fig. 4). Taiwan has instituted a "Nuclear-free Homeland" policy, and the construction of new coal-fired power plants is also difficult. If Taiwan continues to abandon nuclear energy and meanwhile reduce use of coal, its existing nuclear power plants will be decommissioned at the end of their service lives, and no more coal-fired generating units will be installed. In this scenario, existing renewable energy technologies and natural gas generating units must satisfy power demand. With the continued development of renewable energy and natural gas power, renewable energy will account for 35-40% of Taiwan's generating capacity mix, with coal accounting for 5% and natural gas 55-60%.

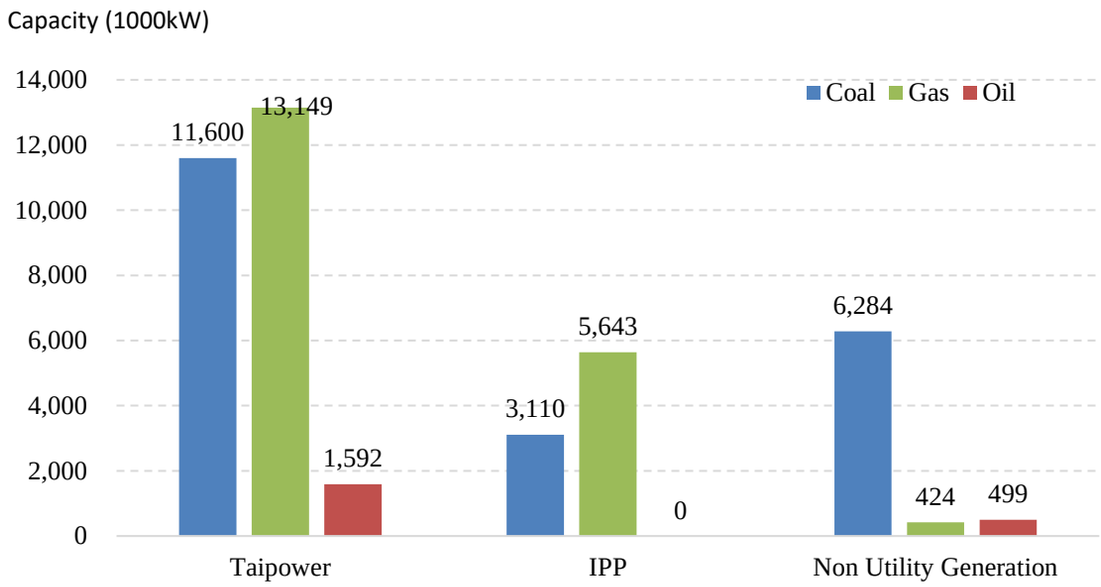
According to installed generating capacity statistics issued by the Bureau of Energy, Ministry of Economic Affairs[4], Taiwan's existing installed generating

capacity totals 60,332 MW, of which thermal generating units account for 70.1% and provide installed capacity of 42,302 MW; this generating capacity consists 26,341 MW from Taipower, 8,753 MW from private power plants, and 7,207 MW from self-used generating equipment. The installed capacity of Taipower's gas-fired generating units is 13,149 MW, which is roughly one-half of the overall capacity of Taipower's thermal power plants (49.9%), and that of coal-fired and oil-fired are 11,600 MW and 1,592 MW, respectively. Thermal generating units at private power plants have an installed capacity of 5,643 MW, and coal-fired capacity of 3,110 MW (Fig. 5).



Source: This study

Figure 4 Planned development of low-carbon energy to 2050



Source: Bureau of Energy, Executive Yuan

Figure 5　Installed capacity of thermal generating units at Taipower and private power plants

Taipower's coal-fired and gas-fired power generating units have been in operation for a combined average of 21.1 years [5], with gas-fired generating units averaging 19.9 years of operation, and coal-fired generating units averaging 22.7 years. The 26 generating units at private power plants have been in operation for 11 to 30 years (average 19.5 years), with gas-fired generating units averaging 19.0 years of service and coal-fired units averaging 21.8 years. There are currently roughly 7 generating units in Taiwan that have been operating for more than 30 years, 18 units for 21 to 30 years, and 18 for less than 20 years (Table 2). In addition, 13 new units are planned for long-term power supply, including 2 coal-fired units and 11 gas-fired units. In consideration that domestic power plants typically operate for more than 40 years before decommissioning, if there are no plans to install more generating units at thermal power plants in the future, approximately 25 existing generating units and 13 newly-installed generating units will still be operating in 2040 (24 gas-fired units, 14 coal-fired units). In 2050, roughly 9 existing generating units and 13 newly-installed generating units will still be operating (15 gas-fired units, 7 coal-fired units).

Table 2 Years of operation of coal-fired and gas-fired generating units at Taipower and private power plants

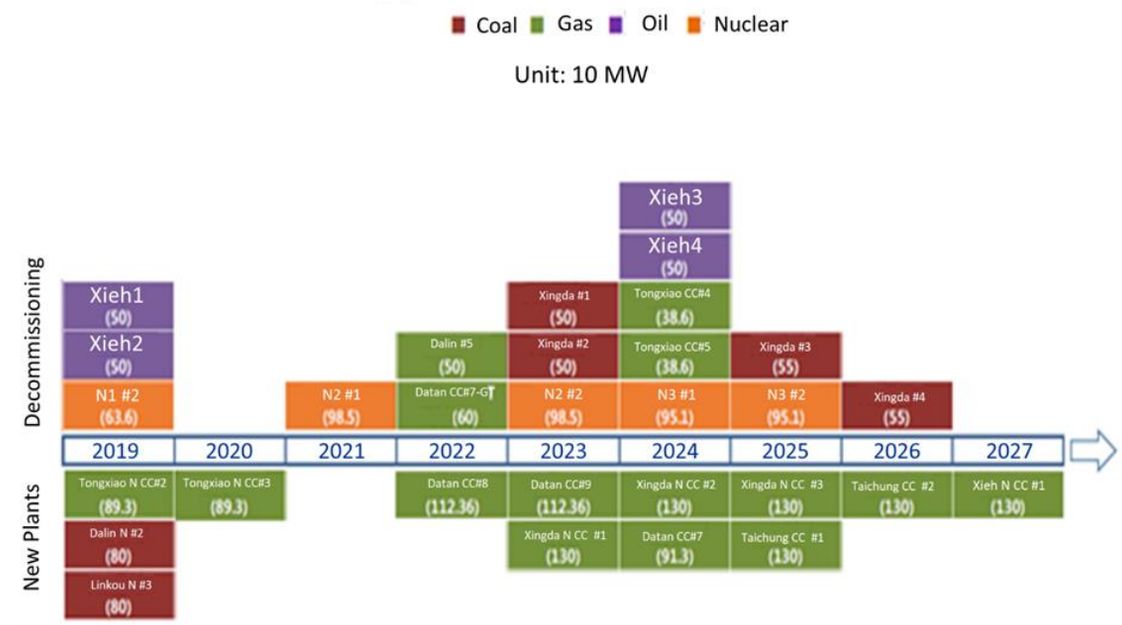
Plant type / Years of operation	Taipower power plants			Private power plants			Total
		Gas	Coal		Gas	Coal	
Total	43	24	19	26	21	5	69
10 years or less	9	4	5	0	0	0	9
11-20 years	9	7	2	14	12	2	23
21-30 years	18	12	6	12	9	3	30
31-40 years	6	0	6	0	0	0	6
More than 40 years	1	1	0	0	0	0	1
Average years of operation	21.1	19.9	22.7	19.5	19.0	21.8	20.5

Source: Bureau of Energy, Ministry of Economic Affairs and Taipower, edited by this study.

In conjunction with the government's energy policy and in consideration of internal and external environmental conditions, Taipower's long-term power development plan (Fig. 6) reflects the expected decommissioning of 8,244 MW in installed thermal and nuclear generating capacity between 2021 and 2027; this plan also calls for the addition of 103.602 MW of installed thermal generating capacity. These new generating units will be installed at the Datan plant (units #7, #8, #9), Xingda plant upgrade (units #1, #2, #3), Taichung plant (units #1, #2), and the new Xiehe power plant (unit #1). Taipower further plans to install 13 new thermal generating units between 2021 and 2027, of which two will be coal-fired and 11 gas-fired.

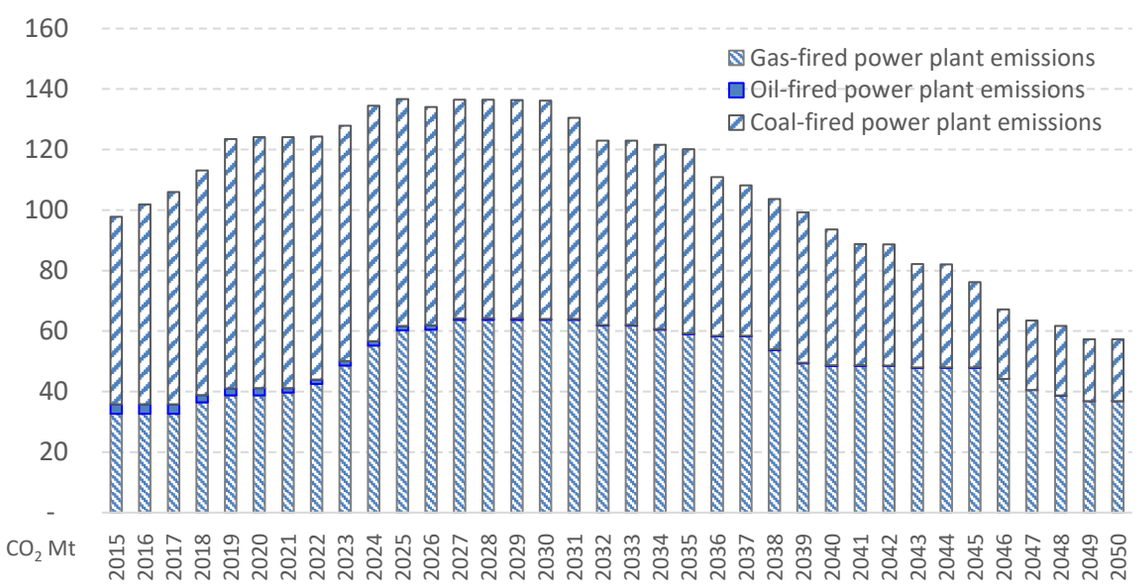
Assuming that the unit carbon emissions of oil-fired generating units are 535(g CO_2/kWh), and each MW of installed capacity generates 1.77 GWh of power; the unit carbon emissions of gas-fired generating units are 440(g CO_2/kWh), and each MW of installed capacity generates 5.73 GWh of power; the unit carbon emissions of coal-fired generating units are 832(g CO_2/kWh), and each MW of installed capacity generates 6.15 GWh of power. The power industry emitted approximately 124.08 million tons of greenhouse gases in 2021. If existing and planned thermal generating units do

not adopt abatement measures, CO_2 emissions will continue to increase, and will peak in 2025 with total emissions of 136.66 million. Total emissions in 2030 would be 136.16 million tons. After some thermal generating units reach the end of their service lives and are decommissioned, total emissions will drop to 93.56 million tons in 2040 and 57.34 million tons in 2050 (Fig. 7).



Source: Taiwan Power Company

Figure 6 Taipower's long-term power development plan



Source: This study

Figure 7 Carbon emission trends at Taipower's thermal power plants

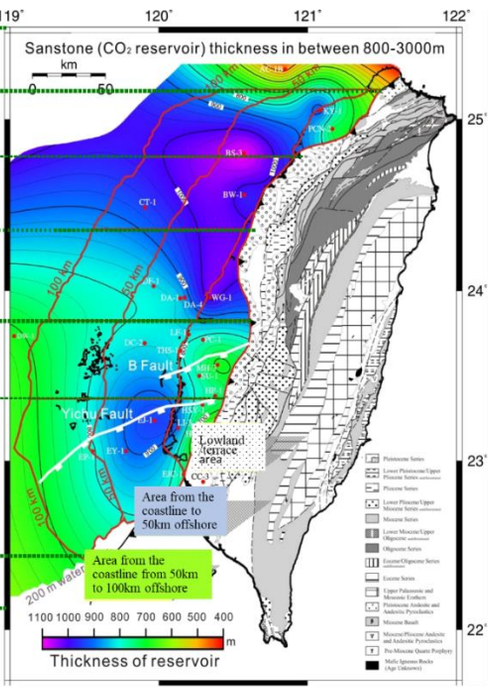
According to the foregoing analysis, if abatement measures are not taken, thermal power plants will emit 93.56 million tons of CO_2 annually after 2040; these emissions will be generated by 24 gas-fired generating units (including 11 newly-installed generating units and 13 existing generating units) and 14 coal-fired generating units (including 2 newly-installed generating units and 12 existing generating units); after 2050, thermal power plants will emit 57.34 million tons of CO_2 annually; these emissions will be generated by 13 gas-fired generating units (including 11 newly-installed generating units and 2 existing generating units) and 3 coal-fired generating units (including 2 newly-installed generating units and 1 existing generating units). According to the recommendations of IEA's roadmap, coal-fired power plants with unabated emissions should be closed by 2040, and those coal-fired power plants that have not reached the end of their service lives in 2040 should adopt carbon capture and storage technology. Accordingly, apart from adopting renewable energy on a large scale, if Taiwan wishes to develop a decarbonized energy system, it must adopt negative emission technologies (NETs) to complete the transition to net zero.

VI. Adoption of carbon capture by thermal power plants in Taiwan

Geological strata in Taiwan suitable for CO_2 storage chiefly consists of terrestrial oil and gas field structures and deep saline aquifer structures along Taiwan's west coast. Prof. Lin Dian-shun of National Central University researched possible sequestration strata and cap rocks near the west coast of Taiwan in 2011, and found that strata on land and at sea in Taiwan area have the potential to store up to 57.4 billion tons of CO_2, with a conservative storage capacity estimate of 16.4 billion tons [6-8] (Fig. 8).

	Area from the coastline to 50km offshore	Storage capacity of lowland/terrace areas (100M tons)
Taipei-Taoyuan area	65	26
Hsinchu-Miaoli area	80	NA
Taichung-Changhua area	89	32
Yunlin-Chiayi area	72	50
Tainan-Kaohsiung area	103	28
Total	410	136

× 100 MT



Source: Andrew Tien-Shun Lin, 2010[9]

Figure 8 CO_2 storage potential of saline aquifers in western Taiwan

According to the analysis of the operating life of existing or future new units, the coal-fired units that have not been decommissioned by 2050 are Linkou (#1, #2, #3) and Dalin (#1, #2), and will generate annual emissions of approximately 20.46 million tons. Gas-fired generating units that have not yet been retired in 2050 will consist of those at Datan (#7, #8, #9), Tongxiao (#1, #2, #3), Xingda (#1, #2, #3), Taichung (#1, #2), and Xiehe (#1); the annual CO_2 emissions of these units will be approximately 34.62 million tons. Oil-fired generating units in 2050 will consist of those at Tashan (#9, #10), which will have annual CO_2 emissions of approximately 21,000 tons. Tashan power plant is located on the offshore island of Kinmen. In view of the plant's size and local geological conditions, negative emission technologies such as DACCS or BECCS can be adapted to offset the power plant's emissions. Large coal-fired and gas-fired generating units will have total emissions of roughly 55.08 million tons in 2050. If carbon capture technology can capture 90% of emissions, it will be necessary to sequester 49.57 million tons of CO_2. The remaining 10%, comprising roughly 5.529 million tons, can be removed from the air using DACCS or BECCS negative emission technologies. In accordance with the foregoing conditions and measures,

Taiwan's thermal power plants can adopt carbon capture technology as outlined below:

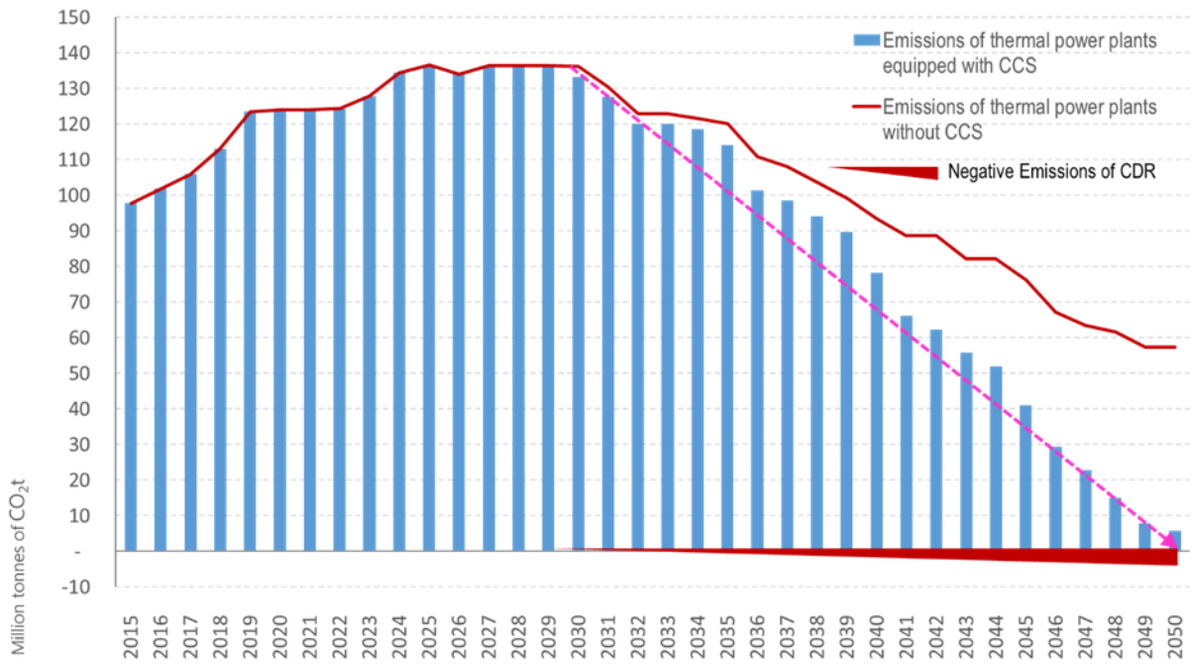
I. From 2025 to 2030, in conjunction with completion of a central Taiwan pipeline and storage sites, thermal power plants in central Taiwan will be the first to adopt CCS technology, which will later be expanded to power plants in Miaoli County.

II. After 2030, following the gradual completion of the pipelines and storage sites needed by power plants in southern Taiwan, the thermal generating units in Kaohsiung area will adopt CCS technology.

III. After 2040, following the completion of the pipelines and storage sites needed by power plants in northern Taiwan, thermal power plants from Taoyuan to Keelung will adopt CCS technology.

IV. In principle, the adoption of CDR technology will begin around 2030, and expand during the next few years, which will allow the goal of net zero to be achieved by 2050.

If CCS technology is adopted in accordance with the foregoing scenario, it is estimated that 2.95 million tons can be stored by 2030, 15.29 million tons by 2040, and 51.59 million tons by 2050. The power sector will need to capture 440 million tons of CO_2 using CCS by 2050, and will also need to capture 14.37 million tons of CO_2 using DACCS/BECCS (see Fig. 9) in order to achieve net zero emissions from thermal power plants.



Source: This study

Figure 9 Carbon emissions of thermal power plants after adoption of carbon capture

VII. Recommendations concerning how net zero power plants can assist enterprises in making a net zero transition

President Tsai Ing-wen announced on Earth Day 2021 that completing a net zero transition by 2050 was the world's goal, and would also be Taiwan's goal. At the same time, such major domestic enterprises as: TSMC, Sino-American Silicon Products, Hon Hai, and China Airlines have pledged to achieve carbon neutrality in compliance with government policy. This shows their willingness to contribute to the earth, and reveals the emphasis that enterprises in Taiwan place on sustainable development. According to the definitions of the scope of direct and indirect emissions sources in the Greenhouse Gas Protocol (GHG Protocol) [9], greenhouse gases generated by equipment, producing power, heat, steam, or cooling (collective termed power), purchased and used by an enterprise constitute Scope 2 greenhouse gas emissions. Energy attribute certificates are contractual instruments representing certain information (or attributes) generated by energy, and do not represent the energy itself. If an enterprise uses a market-based method to calculate its Scope 2 greenhouse gas emissions, it can

use "energy attribute certificates" to calculate the greenhouse gas emissions of the energy that it uses.

Responding to the country's energy transition and the need of enterprises to procure renewable energy, the Bureau of Standards, Metrology and Inspection, Ministry of Economic Affairs announced the "Voluntary Renewable Energy Certification Implementation Regulations" in 2017, which laid the groundwork for the Taiwan Renewable Energy Certificate (T-REC) system. Renewable energy certificates represent property rights to the environmentally-friendly attribute of renewable energy generation; they are necessary tools for substantiating power consumers' renewable energy power use announcements. Enterprises are currently able to rely on the acquisition of renewable energy certificates (T-RECs) to announce their use of renewable energy, and T-RECs can be applied toward national greenhouse gas inventories or voluntary science-based targets (SBTs), which can be deducted from Scope 2 greenhouse gas emissions. After a thermal power plant has adopted carbon capture and storage technologies able to effectively remove greenhouse gases generated by the combustion of fossil fuels, the power generated by the power plant can be considered carbon-free power. The carbon-free power certificate mechanism can convert greenhouse gas emission reductions outside the value chain of power plants that have adopted carbon capture and storage technologies into greenhouse gas reductions within those value chains. If the EU's Carbon Border Adjustment Mechanism (CBAM) is extended to highly complex products and indirect emissions in the future, Carbon-Free Energy Certificate (C-FEC) can be used to reduce the embedded emissions of power used during production processes, and promote a positive circular economy toward net zero (Fig. 10).

Levelized generating cost is chiefly used to compare the economic benefit of different technologies used at different times, such as the comparison of coal-fired and gas-fired power, and can be used to compare costs before and after adopting carbon capture technology. The levelized costs of power plants with carbon capture in Taiwan can be estimated on the basis of the estimation guidelines concerning the levelized cost of electricity (such as guides in the Cost and Performance Baseline for Fossil Energy Plants series) [10-14] among the Baseline Studies published by the US

National Energy Technology Laboratory (NETL). This yields a generating cost of approximately NT$3.06 per kWh for coal-fired power plants with carbon capture. This is an increase of roughly 56.9% compared with the per-kWh generating cost of NT$1.95 at coal-fired power plants without carbon capture. Similarly, gas-fired power plants will have a generating cost of approximately NT$3.50 per kWh (Table 3). There are discrepancies between levelized costs and renewable energy fee rates, which prevent absolute comparisons when compared with onshore wind power with a price of roughly NT$3.6-4.1 per kWh, hydropower of NT$3.4-4.2 per kWh, solar power of NT$4.8-5.5 per kWh, and offshore wind power of more than NT$3.5 kWh. Power plants with carbon capture and storage technology will be competitive with renewable energy.

Source: This study

Figure 10 Use of Carbon-Free Energy Certificate (C-FEC) to create a positive circular economy for net zero

Table 3 Parameters used in the estimation of the levelized generating cost of carbon capture thermal power plants in Taiwan

Parameter \ Plant type	Coal-fired power plants		Gas-fired power plants	
	No carbon capture (0%)	Carbon capture rate (90%)	No carbon capture (0%)	Carbon capture rate (90%)
Net generation (MWe)	1,200	1,200	2,880	2,880
Economic life (T)	40 years		40 years	
Discount Rate (r)	2%			
Capacity factor (CF)	0.85			
Availability rate (U)	0.9489	0.8385	0.9811	0.9362
Fuel price	USD 65.47/ton		NT$13.0229/$m^3$	
Thermal efficiency	0.3904	0.3024	0.5019	0.4429
Hours per year	8,760			
Cost per kWh (NTD/kWh)	1.95	3.06	2.64	3.50

Source: NETL, Taipower, edited by this study.

VIII. Conclusion and Suggestions

The 2050 net zero carbon emissions target was one of the resolutions of the UN Climate Change Conference in Glasgow (COP26). Taiwan's President Tsai Ing-wen announced on April 22, 2021 (Earth Day) that Taiwan had set the goal of achieving net zero emissions by 2050, and Taiwan has drafted a net zero emissions roadmap in March, 2022. The aggregate CO_2 emissions of Taiwan's energy, transportation, and industrial sectors accounted for more than 96% of the country's total emissions in 2020. The country's net zero emissions target can be achieved only if the CO_2 emissions of these three major sectors can be reduced in an economical and effective manner. Among more than 400 emissions reduction pathways suggested by IEA, the most direct and effective strategy should be for the energy sector and the industrial sector, including steel, petrochemical, and cement industries, to adopt CCUS technology. The chief preconditions to the adoption of this technology include safe storage sites, appropriate carbon capture, transport, and storage technology, and sound financial planning. Underground saline aquifers beneath the waters off Taiwan's west coast are estimated to have sequestration capacity of approximately

16.4-57.4 billion tons of CO_2, which will be sufficient to store the current amount of emissions for 50 to 250 years. Taiwan's CO_2 capture technology for coal-fired and gas-fired power plants is not fully mature, and must be acquired from US (such as: Exxon Mobil), Japan (such as: Mitsubishi Heavy Industries) or Germany (such as: Siemens). Such large domestic emitters as Taipower, CPC, China Steel, and Formosa Plastics should organize a Taiwan Team to localize this technology, train specialists, and accelerate various emissions reduction projects.

As for sound financial planning, the government should provide incentives for the adoption of CCUS through tax credits similar to the 45Q tax credits offered under the United States' 2020 Future Act, which consist of a credit of USD 50 for each ton of sequestered CO_2. The government should also draft sunset provisions to expedite the installation of CCUS technology on large fixed emission sources before 2035. Furthermore, the government should quickly implement a Carbon-Free Energy Certificate (C-FEC) system for CCUS adoption, and cooperate with Japan, South Korea, US, and Canada in order to internationalize the recognition of these certificates. The government should also encourage major power users in the semiconductor, flat panel display, steel, petrochemical, cement, and papermaking industries to voluntarily join early CCUS promotion projects. This will ease the pressure caused by the large investments in CCUS equipment needed by heavy emitting enterprises, and encourage the upgrading of industrial hubs.

IX. References

[1] International Energy Agency (2020). Energy Technology Perspectives - Special Report on Carbon Capture Utilisation and Storage -- CCUS in clean energy transitions. 13-14. https://www.iea.org/reports/ccus-in-clean-energy-transitions

[2] Ching-yun Yu, & Ying-jung Chen (2022), Development Trend of Global Negative Carbon Technology (in Chinese), *Taiwan Economic Research Monthly*, 45(1), 110-117.

[3] International Energy Agency (2021). *Net Zero by 2050 A Roadmap for the Global Energy Sector, 3rd revision*. 79-81. https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

[4] Bureau of Energy, Ministry of Economic Affairs (2021, March 9), *Energy Statistics Information System, R.O.C.(Taiwan). Energy Statistics*. https://www.esist.org.tw/database

[5] Taiwan Power Company (2021, May 28), *Overview of nationwide thermal power plants* (in Chinese), https://www.taipower.com.tw/tc/page.aspx?mid=202&cid=130&cchk=f8fb50ec-6465-4637-a2d6-97c05646ada6#b03

[6] Andrew Tien-shun Lin & Jong-Chang Wu (2011). Assessment of Carbon Dioxide Geological Sequestration Amount in Taiwan Saline Formation (in Chinese). *Research project of geological storage of carbon dioxide in Taiwan* (in Chinese).

[7] Li-fu Lin, Chun-to Tso, Yen-haw Chen, Huai-wen Zhang Yun-ting Ma, Qing-xin Chen, L.K. Jiang, Wen-hui Liu (2012), *Conceptual Strategies of Developing CCS Technology Roadmap and Industry Cluster in Taiwan*. Institute of Nuclear Energy Research, Taiwan. ISBN: 978-986-03-2471-6. 65-66.

[8] Shu-yong Ji, Kuo-Shih Shao, I-Jui Lee, Chih-Hao Tan, Chi-Wen Yu (2012), *An assessment of the potential for geological storage of carbon dioxide in Taiwan* (in Chinese), Institute of Nuclear Energy Research, Taiwan, ISBN: 978-986-03-2472-3. 25, 57-58.

[9] Andrew Tien-Shun Lin (2019). Current Status and Perspectives of Taiwan CO_2 Geo-sequestration. *Proceeding of International Workshop on Carbon Dioxide (PC) and Natural Gas to Electricity* (Rev. 4).

[10] World Resources Institute (WRI) (2004). The Greenhouse Gas Protocol, Revision Edition ISBN 1-56973-568-9.

[11] The U.S. Department of Energy (DOE)/ National Energy Technology Laboratory (NETL) (2013). *Life Cycle Analysis: Integrated Gasification Combined Cycle (IGCC) Power Plant* (Rev. 2).

[12] National Energy Technology Laboratory (NETL) (2019). *Cost and Performance Baseline for Fossil Energy Plants vol 1: Bituminous Coal (PC) and Natural Gas to Electricity* (Rev. 4).

[13] International Energy Agency (IEA) and the OECD Nuclear Energy. Agency (NEA) (2020). *Projected Costs of Generating Electricity 2020*. https://www.iea.org/reports/projected-costs-of-generating-electricity-2020

[14] National Energy Technology Laboratory (NETL) (2021). *Cost Estimation Methodology for NETL Assessments of Power Plant Performance*.