2024

Taiwan's Energy Puzzle

台灣未來能源拼圖

CETA
Clean Energy Transition Alliance

Executive Summary

Taiwan is a tiny country. In terms of land area we are on par with Estonia, but with 17 times the population. Furthermore, we are home to power-hungry tech manufacturers such as chipmaker Taiwan Semiconductor Manufacturing Company (TSMC), which makes around 90% of the world's high-end chips. In fact, more than half of Taiwan's power usage is industrial, making it difficult to decouple from economic growth. This raises a number of questions.

First, take the grid, which accounts for 32.1 % percent of Taiwan's primary power use. To achieve a significant reduction in our carbon footprint, we must "electrify everything," meaning that grid could double or even triple in size , a reality even some professionals in the field have yet to address.

Policymaking seems similarly unrealistic; Taiwan's Pathway to Net-Zero Emissions in 2050 roadmap (hereinafter, the "Roadmap") assumes the country's growth in energy demand to be almost flat between now and 2050. Meanwhile, electricity demand is projected to increase by only 50% between now and 2050, an average of around 2% per year. This seems out of step with the government's ongoing efforts to encourage manufacturers to set up shop in Taiwan, providing incentives especially for China-based Taiwanese-owned businesses to bring

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https://www.moeaea.gov.tw/ECW_WEBPAGE/FlipBook/2022EnergyStaHandBook/index.html#p=74

https://www.moeaea.gov.tw/ECW_WEBPAGE/FlipBook/2022EnergyStaHandBook/index.html#p=38

This is the finding of some US-focused research on electrification. See https://netzeroamerica.princeton.edu/?explorer=year&state=national&table=2020&limit=200

https://ws.ndc.gov.tw/Download.ashx?u=LzAwMS9hZG1pbmlzdHJhdG9yLzExL3JlbGZpbGUvMC8xNTA0NS8xMzdmMjYyMS01NmQ4LTQ0MjctODkxZS05MDQ1MjdjZmMzMzYucGRm&n=VGFpd2Fu4oCZcyBQYXRod2F5IHRvIE5ldC1aZXJvIEVtaXNzaW9ucyBpbiAyMDUwLnBkZg%3d%3d&icon=.pdf

production back home . Is it realistic to expect no growth in total energy demand? And is the relatively modest 50% increase in the grid enough for Taiwan to decarbonize by “electrifying everything?”

Accepting the Roadmap’s projections as is, 60-70% of Taiwan’s decarbonized grid will come from renewables by 2050. That raises questions about how to use renewables effectively to provide a reliable power supply. What level of renewable capacity would be necessary to feed this demand? If they are intermittent renewables, which baseload energy sources – such as nuclear, which has been phased out by the government – should be used? Linking renewables to the grid, it is not guaranteed that Taiwan’s isolated island grid could cope with these power fluctuations. The Roadmap assumes that achieving 9-12% hydrogen and 20-27% natural gas with Carbon Capture Utilization and Sequestration (CCUS) technology is feasible, an assumption that needs assessing. Even if it holds water, serious and immediate progress is needed to make it a reality.

In order to answer these questions, Part 1 of this report will examine a number of the alternative energy resources currently available to Taiwan. This includes energy sources that are already well-known like solar and wind and nuclear, sources that are getting its start like geothermal and hydrogen, and and even radical future solutions like Ocean Thermal Energy Conversion (OTEC) and Carbon Dioxide Removal (CDR). We are fortunate to have the involvement of top voices from industry to consult on, and in some cases, author those pieces.

In Part two, we will examine how the pieces of the puzzle can be put together to address Taiwan’s energy demand. Authored by Finnish energy analyst Rauli Partenan, Part two entertains different scenarios for Taiwan’s energy future and game out how different decarbonization roadmaps might unfold. We will try to anticipate future pitfalls and address the pros and cons of each of our options. For instance, if Taiwan’s power usage does not stay flat but increases sharply, how does that affect our assumptions and projections? By examining different scenarios, we hope to present the trade offs of our various future energy choices with greater clarity and connect our lofty 2050 goals with the facts on the ground.

There are many choices in front of us as a country when it comes to our energy transition, but a key piece of the puzzle is definitely this: is Taiwan going to see a nuclear exit soon or a nuclear renaissance? As Partenan shows compellingly through four possible scenarios, it will be very difficult for Taiwan to follow the current plan as outlined by the NDC. Our path can be substantially smoothed by the life extension of our current nuclear power plants, or even – in the most ambitious scenario – with new-build nuclear to support the rapid and ambitious buildout of renewable energy that Taiwan undoubtedly needs.

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The challenge of the energy transition is one that humanity will have to live with for generations. Despite our best efforts, experts are increasingly pessimistic about the prospect of keeping global warming to 1.5 degrees or less. But there is no simple binary of passing or failing; every reduction in emissions reduces the impact on our environment and well-being. Taiwan's goal of reaching Net Zero by 2050 must similarly be put in that context. We hope that these scenarios will help bring a greater sense of clarity to the enormous task at hand of taking Taiwan from number 61 (out of 67) on the Climate Change Performance Index to a low-carbon country without jeopardizing our energy security. There is no right answer, only trade-offs that we must make clear-eyed choices about.

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Energy Security in Taiwan

A blessing and a curse

Jordan McGillis

Taiwan's manufacturing-driven economy is among the world's most productive — and its most energy-intensive. As an island dependent on energy imports, Taiwan faces acute energy security risks that could severely disrupt its output and normal functioning. Of particular concern is Taiwan's electricity sector. Taiwan's economy is more electricity-intensive than those of contemporaries like South Korea, Japan, and Germany. Comparing units of electricity consumption per unit of economic output — here in terms of kilowatt-hours per U.S. dollar (kWh/$) — shows that Taiwan's economy has an electricity intensity exceeding South Korea's by more than 12%, 0.348kWh/$ for Taiwan vs. South Korea's 0.309kWh/$, based on International Energy Agency and World Bank figures.

Japan and Germany log kWh/$ figures of 0.196 and 0.124, respectively. Taiwan's electricity intensity can be attributed to manufacturing's sustained preeminence. Japan and Germany have experienced relative declines in manufacturing as a portion of their output, putting the sector below 20% of total productivity now in both countries; South Korea remains more manufacturing-centric at 25% ; Taiwan tops them all at 34%.

Taiwan's industrial sector consumes the lion's share of the island's total electricity, more than 55% today compared with less than 50% 20 years ago. Specifically, the electronics manufacturing sector, led by chip giant Taiwan Semiconductor Manufacturing Company

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https://databankfiles.worldbank.org/public/ddpext_download/GDP.pdf#:~:text=Gross%20domestic%20product%202021.%20Gross%20domestic%20product%202021.,Italy%202%2C107%2C703%209%20Canada%201%2C988%2C336%2010%20Korea%2C%20Rep.

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https://www.moeaboe.gov.tw/ECW_WEBPAGE/FlipBook/2021EnergyStaHandBook/index.html#p=74

(TSMC), consumes a high percentage of Taiwan's total available power — more than 20% for the sector as a whole and more than 5% for TSMC alone, according to the Bureau of Energy.

The growth of this sector has created prosperity while simultaneously driving an almost 50% increase in electricity consumption relative to population over the past 20 years. Maintaining Taiwan's electronics manufacturing, its broader industrial prowess, and its normal, everyday consumption of electricity depends on stable and secure energy supplies.

A blessing and a curse

Coal and natural gas anchor Taiwan's electricity mix today, though plans for Taiwan's electricity mix aim to shrink coal and increase natural gas consumption. While such a plan has advantages, energy security is not among them. Given its physical properties, natural gas is difficult to store, and generating electricity with it depends on just-in-time delivery. As of 2022, Taiwan's two existing natural gas import terminals held just two weeks' worth of the fuel in storage. The third natural gas import terminal will improve the situation when it begins operations, as will subsequent additions. However, the new terminals will not alleviate the inherent risks of maritime imports.

Coal, while also dependent on maritime imports, is easy to store and thus provides a better hedge against contingencies such as a blockade against Taiwan's ports. Taipower in its standard operations already stores six weeks' worth of coal or more. Maintaining coal-fired generation capacity and expanded coal stockpiles would enhance Taiwan's energy security, even if coal's role in regular operations declines. The 100-day coal storage target vocalized by deputy economic minister Tseng Wen-sheng in 2022 is a strong first benchmark.

Considering a re-incorporation of nuclear power into Taiwan's plans would also be wise. Nuclear power plants routinely store 18 months' worth of fuel on site, an advantage made possible by its dense nature. Moreover, nuclear power comes with none of coal's emissions externalities. Reversing the current nuclear phaseout plan, restarting decommissioned reactors, and putting the Lungmen nuclear power plant into service could yield nearly 8GW of total dispatchable nuclear capacity, equivalent to almost 20% of Taiwan's electricity peak demand.

Wind and solar are also intriguing candidates for power generation, given Taiwan's unique risks and geography. As distributed power generation sources, they do not require ongoing imports of fuel and solar; they are both, however, subject to weather conditions and are therefore not viable as replacements for the baseload power provided by today's coal fleet without technological leaps in battery storage.

Given the political plans in place, Taiwan will become more dependent, via higher natural gas usage, on imports in the coming years. Taiwan has a similar import dependency on oil, the resource that provides most of its total energy supply, as the leading transportation fuel. Lacking domestic crude oil production, Taiwan imports more than 99% of its oil supply via maritime

tanker. Most crude oil imports arrive at the ports of Kaohsiung, Keelung, and Mailiao, and are refined at facilities in Taoyuan, Mailiao, and Dalin.

https://www.moeaboe.gov.tw/ECW_WEBPAGE/FlipBook/2021EnergyStaHandBook/index.html#p=76

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How to improve Taiwan's energy security

Shoring up Taiwan's stockpile planning for crude oil is vital to the island's energy security. To build resilience against the possibility of a blockade that prevents imports for an extended period, Taiwan must set aside its polarized energy and environmental debates and build consensus around robust strategic oil stockpiles. It should learn from the examples of South Korea and Japan, which have better established stockpile regimes and partnerships with oil-producing countries. South Korea arranged a partnership with Kuwait in 2006, under which Kuwaiti-owned oil is stored on Korean territory; South Korea has first right to buy the oil in the event of emergencies.

Beyond such storage arrangements, an idea proposed by United States Army Captain Merlin Boone is for the Taiwanese government to subsidize the development of refining capabilities on the island's east coast, in the vicinity of Hualien or Keelung, where it could link into existing infrastructure. Boone argues that a new focus on east-coast infrastructure would enhance "supply chain survivability against military action." On a similar theme, Taiwan should consider building a fortified strategic oil reserve under state management, rather than commercial management, as is the norm for oil storage at this time, for emergency use.

Such plans would not be without tradeoffs. Taiwan's industrial performance and day-to-day functioning has flourished with minimal crude oil and natural gas storage till now. Building new oil and gas import and storage facilities would be costly, taking money away from other valued purposes. What the energy security they would provide is worth is a question upon which the Taiwanese body politic must deliberate.

Jordan McGillis is the economics editor of City Journal, an adjunct fellow at the Global Taiwan Institute, and the former deputy director of policy at the Institute for Energy Research.

https://globaltaiwan.org/2024/02/geopolitics-and-energy-security-in-taiwan-a-refined-analysis/

The Promise of Geothermal for Taiwan

Paddy Stephens, in collaboration with Claire Lai from Baseload Capital.

Located on the "Ring of Fire," Taiwan has 33.6GW of potential geothermal energy capacity, almost 2.5 times the current installed renewable capacity, according to the Central Geological Survey. Unlocking the full capacity of its geothermal reserves would allow Taiwan to satisfy its current level of electricity demand. This natural asset is particularly useful both as a rare example of a green baseload energy source and – given Taiwan's geographical constraints – one for which land-use intensity is low. Recognizing the value of a non-weather-dependent renewable source, the government is keen to develop this industry, and its most recent planning aims to reach 6GW capacity by 2050. This section discusses the current momentum in the geothermal industry, its small scale, and the key factors holding it back.

The state of geothermal in Taiwan

Taiwan's geothermal industry is still in its infancy, and much of the country's geothermal potential remains untapped. Discussion of geothermal around New Taipei City started in the 1960s, but technical issues of fluid acidity, which current technology can now overcome, made this unviable at the time. The country's first geothermal power plant opened in the 1980s, but shut down after only 12 years due to inefficiency. Recent years have seen a renewed impetus towards geothermal development, including the inauguration of Taiwan's first operational geothermal plant at Qingshui in November 2022. Taiwan's first commercial power plant drawing energy from a volcano opened in Jinshan, October 2023. This has been supported by a clear recognition from the government of the importance of geothermal, with Taiwan's Ministry of Economic Affairs in September 2022 pre-announcing draft amendments to the Renewable Energy Development Act that would regulate geothermal exploration, development, and production. And in January the next year, the ministry hosted the first- ever Taiwan International Geothermal Conference. The Pathway to Net-Zero Emissions in 2050 roadmap sets a target of 3-6.2GW of geothermal power generation, replacing almost ⅓ of coal-fired power units.

Yangmingshan National Park. Photo source: weichen_kn/ Flickr

Despite progress, geothermal generated a paltry 0.007% of Taiwan's electricity needs from January to August 2023. Taiwan has a current grid-integrated capacity of 7.29MW, as well as 52.66MW in planned installation capacity. The geothermal electricity capacity target of 200MW in 2025 was reduced in April 2022 to 20MW, and even reaching this reduced target by 2025 is "doubtful" according to recent research.

As for the future of the geothermal industry, developers remain skeptical of Taiwan's desirability. In contrast to the solar and wind industries, there has only been one foreign investment in geothermal electricity so far in Taiwan. Most damning is the experience of independent heat power producer Baseload Power Taiwan's CEO, who says the company "came into Taiwan in 2019 with a goal of investing over a billion U.S. dollars in geothermal energy development. Most of that investment has now gone to other countries." Claire Lai, Asia Regional Marketing Director at Baseload Capital, has acknowledged the government's recent efforts, but says that "if we want to achieve the ambitious energy targets by 2050 in Taiwan, the government needs to speed things up." She highlights the current "momentum" in Taiwan's geothermal industry and emphasizes the need to learn from mature geothermal markets. Doing so would help Taiwan avoid certain mistakes and tailor the industry to fit Taiwan's landscape and market context.

Yangmingshan National Park. Photo source: Ludovic Lugeibt/Flickr

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What's holding the industry back?

1 **Natural limits:** While hot springs are found across Taiwan, suggesting rich geothermal reserves, this heat can only be converted into electricity at sufficiently high temperatures. Maintaining the efficiency of geothermal wells also requires sustained temperatures. As a result, only certain areas in Taiwan are currently suitable for geothermal energy generation – though this might change in the future (see p. Enhanced geothermal section).

2 **Land zoning:** Land is often reported to be the main concern of investors in Taiwan. There are two separate sets of land use issues. One is land zoning: the Taiwanese government regulates how certain land can be used, especially on steep, forested land, often because of environmental concerns. Consultation is needed between the government and industry on whether small-scale projects such as geothermal, which work to minimize environmental damage, could be permitted in national land planning.

3 **Community engagement:** The second land issue is that many geothermal potential areas overlap with Taiwan's indigenous territories. The transition of land rights across generations therefore presents challenges for investors. Baseload Capital's Lai points out that geothermal has lots of direct uses in the surrounding economy, and therefore offers benefits to both local communities and developers. She calls for more support from the government in facilitating dialogue between developers and communities. The government also has a role in conveying correct information about geothermal energy, given some misconceptions among the public that may lead to opposition.

New Zealand, which has one of the most advanced geothermal sectors in the world, faced some of the same land use questions with its Maori people. One useful framework is partnerships in New Zealand with Maori trusts, which is "crucial" to the sector's success. Such partnerships allow geothermal plants to be constructed in a way that prioritizes sustainable resource use that benefits their people.

4

Upfront risks: Geothermal also has particularly high upfront financial risks compared to wind and solar. Two specific aspects put off investors: surveys and feed-in tariffs. Possible improvements to these could make investment in Taiwan's geothermal significantly more attractive.

For example, the Geothermal Incentive Program offers maximum funding of NT$100 million and 50% of the exploration cost in each case, for a limited implementation period of 5 years. Baseload Capital's Lai suggests adjustments to the design of the incentive program, including streamlining the process and reducing paperwork, considering its very initial phase on project development, and more effective structure to actually share the cost and risk on exploration work.

Another important element is geological surveys. Taiwan's government has already taken action on this, launching a geothermal exploration platform and publicly releasing exploration reports and drawings since 1966. Greater availability of geothermal data would significantly boost the development of the industry.

One suggestion is to create a national database for geothermal exploration, which would provide references for site selection for geothermal power extraction. New Zealand's government worked to map potential sites for geothermal energy development from the 1950s to the 1980s, accelerating the building of power plants. Other governments, including the U.S., Japan, and the Philippines also take on a more significant role at the exploration stage.

5

Feed-in tariffs: The geothermal energy feed-in tariff (FiT) guarantees in advance the price that producers can sell the electricity they generate at under a long-term contract. The government offers its fixed 20-year FiT and tiered FiT rates as a promotion strategy, including an additional 1% bonus on the FiT for profit-sharing with indigenous communities. Despite being "extremely high," the effects of high FiTs are low, because other costs are high in Taiwan. Claire Lai points out that though the FiT is lower in many mature markets, such markets also have clear resource rights and licenses, streamlined processes for geothermal projects, a greater amount of publicly available data, greater public acceptance, an established geothermal supply chain, and other factors that reduce the initial costs for the developer. A higher FiT, possible in Taiwan given its state-owned electricity market, would increase the attractiveness of Taiwan as a place to develop geothermal while other costs are reduced and processes are improved.

6

Technology: Technology can be used to reduce costs, including deep drilling and high-pressure hydraulic fracturing (see section on enhanced geothermal below).
At three geothermal power plants, Taiwan's self-developed geothermal power generation tech is used, but limited scale and drilling technology mean that the single-well production capacity is about one-fifth of the international average .

7

7. Legislation: This overarching issue is what Baseload Capital's Lai highlights as the key issue holding back the development of geothermal in Taiwan. Much of geothermal development has been regulated by hot spring laws, meaning the process to build a geothermal plant is complex, unclear, and time consuming. The government is working on improving this process, including establishing in 2022 a single service window to assist developers with regulatory disputes. Importantly, the Geothermal Subsidiary Law pre-announced in January 2024 standardizes application procedures for geothermal energy generation, offering accelerated review mechanisms that remove the need for the original hot spring development permitting processes. In addition, the 2023 Renewable Energy Act (hereinafter, REA) aimed to "specify the administrative procedures of geothermal development." In particular, it sought to improve regulatory certainty regarding 1) exploration permits, 2) energy development permits, 3) water rights issues, 4) obligations to provide relevant data to the government, 5) indigenous people.

However, it has been argued that the REA fails to facilitate project development and might just add red tape for developers. In particular, articles relating to indigenous people do not really clear up the regulatory uncertainty. As one research team put it, "on closer examination, it is revealed that this article only 'repeats' and refers to the public consultation and consent clause of Article 21 without additional provision." No legal solution has yet been offered to conflicts with indigenous people resulting from the development of geothermal and small hydropower electricity.Claire Lai calls for stakeholders, including government and developers, to work together on creating more appropriate laws for geothermal.

Turkey's rapid expansion of geothermal capacity offers one legislative model, using proactive government initiatives, tailored legislation, and streamlined procedures for land and environmental assessments. Chief Executive of the New Zealand Geothermal Association Kennie Tsui emphasizes the importance of robust laws and regulations for the industry. In New Zealand, the central government sets overarching policies and strategies, while local governments are responsible for consenting policies, monitoring, and handling license renewals. Tsui has explained that "a lot of investors favor this kind of setup, which gives local governments the authority to bring in panels of experts or undertake public consultations. It's a really effective way to engage not just with the applicant [of a geothermal project] but also with the public."

The possibilities of Enhanced Geothermal

Paddy Stephens

A new generation of "enhanced" geothermal systems promise to overcome challenges to and improve the energy source, with broad possibilities from reduced project costs to grid reliability enhancements. Discussion of the large-scale commercial viability of such technologies at this early stage is, of course, speculative. Yet it remains instructive, especially given that Taiwan's government envisions using such "visionary key geothermal technologies" in Phase 3 (2030s) of its geothermal plan. Three examples are discussed below, along with some overall possible considerations in future planning.

1

Rapid scale-up through horizontal drilling

As outlined above, many of conventional geothermal's challenges are financial, and so cost reductions would greatly increase the viability of projects within the industry. Fervo Energy proposes using drilling techniques developed in the shale industry. In particular, horizontal drilling allows for drilling of multiple wells in one location, thereby reducing drilling costs while allowing improved access to challenging-to-reach geologies. The idea is that drilling wells in a condensed area should offer "geologic, technical and experience learning curves," which "improve project economics over time." All of those advantages of horizontal drilling offer the promise of replicating "dramatic learning curve cost-reductions" seen in the shale industry in the last two decades. Initial results are promising, with a commercial-scale demonstration in Nevada showing an 18% reduction in total drilling days between the first and second horizontal wells. It should be noted, however, that though within safe levels based on U.S. Department of Energy Protocol, a rise in seismicity rates was observed, meaning that research would be needed to assess how applicable this would be to Taiwan, given its tectonic risks. Even if experts judge it to be safe, it may be challenging to convince local populations, and some local resistance could be conceivable if communication is not handled carefully.

2

Overcoming limited site number with the Eavor-Loop™

Another issue is the limited number of possible geothermal sites, which an approach demonstrated by Eavor Technologies Inc. may be able to overcome. The Eavor-Loop™ will use conduction instead of convection in a closed-loop geothermal system, which circulates a fluid that "retrieves heat from the surrounding rock via conduction," acting like a "reverse radiator" to transfer heat. Such a system does not depend on direct access to hot aquifers or fracking techniques and requires less specific conditions. The company claims such a system "can be created practically anywhere." Eavor's first commercial-scale project in Germany is due to start producing energy by 2024 and reach full capacity by 2026. Eavor has €1 billion in funding to build another five geothermal projects in North America and Europe.

6

A geothermal battery?

Alongside cost reductions, enhanced geothermal offers possibilities for energy storage and grid management. Next-gen geothermal plants can ramp up or down generation in a few minutes and can "run for as long as necessary to ensure the reliability of the grid, thanks to advanced well flow control and power system setups." Fervo has developed a system with early results indicating that it could store energy for hours or days and then deliver it back over a similar period, "effectively acting as a giant and very long-lasting battery." Early experiments have been positive, but the commercial viability of this still remains to be proven.

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Issues and considerations

Despite their clear promise, such enhanced approaches to geothermal are in their infancy, and still face a number of issues that should be carefully considered.

1

Capital-intensity: According to 2022 data, a next-generation geothermal project in 2022 would require more than US$8.7 million/MW in capital expenditure, compared with US$1.8 million/MW for onshore wind and US$1.1 million/MW for solar plants. In general, "capital expenditures rise as temperature and depth increase." One problem is the high upfront financing costs of geothermal, with "a roughly 15% weighted average cost of capital at the pre-drilling stage, compared with 5% for wind and solar projects."

2 **Scalability:** The next-gen projects that have been proven as technically feasible are small-scale. How well they scale in terms of effectiveness, ability, and safety is unclear. “The commercial projects to be developed in the coming years could provide more insights.”

3 **Seismicity:** Further research is required on the seismic risks specifically of unconventional oil and gas industry techniques at a commercial scale in Taiwan.

4 **Regulatory frameworks:** These would need to be designed to offer low project approval timelines and low financing barriers to increase enhanced geothermal investment and offset the issue of capital intensity.

Concluding Remarks

Taiwan’s potential for geothermal energy capacity is of significant natural benefit in tackling its energy puzzle. The rapid growth of offshore wind power in the country demonstrates “a good synergy” between policy making and industrial investment, which is encouraging for the geothermal industry. To make the most of this green baseload energy source, Taiwan needs to boost investment and scale in its geothermal industry. As a final point, communication is a vital part of this process. Past policies in private green energy development neglected effective communication with stakeholders, resulting in public opposition, prolonged timelines and increased project risks. Policymakers must seek to engage effectively with stakeholders to ensure the success of geothermal in Taiwan.

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The Transition to Green Energy: Navigating New Challenges with Green Financing

Steven Chen, Angelica Oung

Taiwan's transition to green energy brings new challenges in infrastructure financing. Traditionally, Taiwan's local businesses and banking sectors are used to funding significant infrastructure projects, including transportation and water systems, through mechanisms such as public-private partnerships (PPPs). However, green energy projects, especially offshore wind, introduce complex challenges that necessitate unfamiliar financial models and the involvement of international partners.

Case Study: A Taiwanese offshore pioneer

A prime example of this transition is a Taiwanese specialist manufacturer of materials that include resins used in the manufacturing of offshore industry components. However, when the company ventured into developing Taiwan's first offshore wind farm it faced skepticism from shareholders and banks.

From this firm's perspective, being involved in a growth industry still in its infancy in Taiwan has the potential to yield enormous rewards. But the project's sheer scale and its divergence from the company's core business caused concern from shareholders and financial institutions. The project's capital expenditure (CAPEX) significantly exceeded the company's market capitalization, highlighting the perceived risk.

Aligning Vision with Caution

To bridge the gap between the company's ambitious vision and the cautious stance of its shareholders and banks, a strategic organization was necessary. The firm established a new entity dedicated to its offshore wind ventures under the umbrella of a holding company that also contained the materials manufacturer. The restructured corporate framework enabled the inclusion of equity stakeholders such as Macquarie and Ørsted, bringing financial support as well experience and credibility to the new offshore wind entity. Their involvement was instrumental in launching the project as a Special Purpose Vehicle (SPV), culminating in the successful establishment of Formosa 1, Taiwan's first commercial offshore wind farm.

Lessons learned: The importance of strategic partnerships

Swancor's journey illustrates the critical need for a suitable corporate structure and strategic selection of international partners in executing large-scale and complex projects like offshore wind farms. The development lifecycle of offshore wind projects demands a dynamic partnership model, evolving to incorporate various players with the requisite expertise and resources at different stages of the project's development.

Equity finance vs. debt finance in offshore wind projects

1

Special Purpose Vehicles (SPVs): A brief overview

Special Purpose Vehicles (SPVs) are subsidiary companies created for a specific purpose, often to isolate financial risk. In the context of offshore wind projects, SPVs are critical for securing financing without directing the parent company's financial risk profile. They allow for the separation of project assets, liabilities and operations, providing a legal and financial structure that facilitates project financing.

2

Financing structure: Blending Equity and Debt

For a typical offshore wind project of 500MW in size, the total cost can reach approximately NT$100 billion (around US$3 billion). Financing these projects involves a blend of equity finance and debt finance through an SPV. Equity holders, including the project's originators, often contribute about 30% of the capital cost. The remaining 70% is secured through debt financing from banks, pension funds, and other financial entities.

This highly leveraged financial model underscores the necessity for a predictable revenue stream. Banks and financial institutions require assurance on their investment, often preferring mechanisms like feed-in tariffs (FiTs). FiTs, guaranteed by the state or entities like Taiwan's Taipower, promise a favorable rate for electricity purchased over a 20-year period, providing the financial stability needed for such large-scale investments.

3

The equity stakeholders' perspective

On the equity side, stakeholders typically include investment funds like Copenhagen Infrastructure Partners (CIP), Blackrock, and Global Infrastructure Partners (GIP), as well as utility developers such as Iberdrola and RWE. These equity holders are prepared for the high-risk, high-reward phase of wind farm construction, accepting the potential for cost overruns and other challenges as they develop the project. Their strategy often involves selling down equity post-construction to recoup and reallocate capital.

These investors usually aim to exit the project once it achieves financial close or upon reaching its Commercial Operating Date (COD), the point at which the project is operational and generating revenue. The risk profile of the project decreases significantly after COD, attracting investors like pension funds interested in stable, long-term returns.

4

Government regulations and market dynamics

Taiwan's regulatory stance requires initial sponsors to retain a minimum of 50% of their original equity stake, contrasting with the international norm of sponsors potentially reducing their stake to as low as 5%. This regulatory requirement reflects the government's desire for project initiators to maintain significant involvement, creating a tension between government expectations and market practices.

Lifecycle of a wind farm: Development to financing

1

Initial development phase

The project life cycle begins with the original developer securing permits and approvals for construction. This phase involves substantial groundwork, including environmental assessments and community engagement, to obtain the necessary permissions for development.

2

Inviting strategic partners

Upon securing the construction permit but before financial close, the developer seeks strategic investors to provide the equity portion of the financing. This stage often involves inviting funds and other experienced players to invest in the project, setting the stage for debt financing.

3

Securing debt financing

The equity holders then seek the remaining 70% of financing through debt. For Taiwan projects, it is desirable to engage with a mix of European and Taiwanese banks to lower the currency risk of participating financial institutions.

The syndication loan process is usually initiated by an experienced international entity such as an export credit agency. However, many Taiwanese banks have been involved in syndication loans despite their relative unfamiliarity with the process.

3

Financial instrumentation and risk management

As the project matures and de-risks, the financial ownership of the wind farm further evolves and becomes an instrument traded dynamically among institutions. This flexibility allows entities to align their investment with their risk tolerance and financial goals over the project's lifespan.

The shift to CPPAs in Taiwan's offshore wind: Challenges and prospects

a

Transition from FiTs to CPPAs

Taiwan's government facilitated the initial development of offshore wind projects through generous FiTs, providing a secure revenue stream for developers and confidence for financiers. However, with Round 3 projects slated to commence construction in 2026, the FiTs have been withdrawn in favor of an auction-only model. Furthermore, the auction is structured to encourage developers to bid low in order to secure a project and to generate the real revenue stream through Corporate Power Purchase Agreements (CPPA).

Taiwan's prominent tech sector uses a significant amount of the nation's electricity output, with chip giant Taiwan Semiconductor Manufacturing Company (TSMC) alone using 7.5% of the grid in 2022. In line with the global trend for tech companies, many Taiwanese firms have pledged to switch over to using renewable energy only. TSMC, for example, took the RE100 pledge to reach 100% renewable energy by 2040.

These supply-chain decarbonization commitments put tremendous pressure on Taiwan's tech companies to purchase renewable energy at a premium.

b

The CPPA model: Financial viability concerns

Despite the willingness of tech companies to engage in long-term CPPAs, financial institutions are wary regarding the sustainability of premium payments over such extended periods for extremely large projects like offshore wind farms. Among Taiwan's tech giants, only TSMC is deemed sufficiently creditworthy for a 20-year CPPA, leaving smaller yet significant tech firms unable to sign such agreements due to concerns over their creditworthiness.

To mitigate this, the government has proposed an 18-month guarantee in case of unexpected termination of a CPPA. This "bridge" period is supposed to allow the project time to secure a new CPPA to take over the payments. However, developers and financiers consider this measure inadequate considering offshore wind's substantial investment requirements.

C

The problem with zero: Implications of Taiwan's auction system

In Europe, offshore wind projects have been successfully weaned off FiTs, significantly relieving the financial burden on the state of supporting the industry. Instead, projects are awarded using an auction system where developers competitively bid as low as possible. Some developers bid zero for auction because they are so confident that they can secure a good price for their output with alternative mechanisms such as PPAs.

Taiwan has emulated this model, moving from a mix of FiTs and auctions in Round 2 to withdrawing FiTs altogether in Round 3 in favor of auctions. In addition, a very low ceiling of NT$2.49 was set for the auction price. It is impossible to recoup the cost of building a wind farm in Taiwan at the maximum auction price, incentivizing developers to bid zero to secure the project while opting to sell their electricity via CPPAs to tech companies. However, this strategy creates a vulnerability for the future financial soundness of their project.

The European market was able to transition successfully from FiTs to an auction system and even allow for zero price bidding because the electricity market in Europe is liberalized and there is always a market for power. Thus if a wind farm in Europe faces a collapsing PPA, they always have the option of selling their electricity output into the market at the spot price, providing a financial safety net for the project and their banks. This stream of revenue might not completely replace the PPA, but functions as an offtaker of last resort.

In Taiwan, however, there is no such safety net. While the Renewable Energy Development Act of 2009 allowed private developers to sell their power through PPAs, there is no separate wholesale market in Taiwan for them to sell their power into as the electricity system is managed by the state-owned monopoly utility Taipower.

This quandary prompted lead industry group Taiwan Offshore Wind Industry Association (TOWIA) to lobby for Taipower to be the offtaker of last resort. They propose a mechanism for Taipower to purchase electricity from wind farms with terminated PPAs at the avoidance cost of NT$2.29, providing a safety net for Taiwan's projects.

TOWIA's proposal has been met with skepticism due to the moral hazard it presents: If developers wanted the safety net, why did they bid zero in the auction instead of the avoidance price?

d

Global market gyrations and the new reality of offshore wind

Despite the objection to renegotiating a deal after the conclusion of an auction, there is substantial risk that Taiwan's Round 3.1 projects cannot proceed as planned.

In addition to the credit risk issue, the cost of Round 3 projects have soared on the back of commodity price gyrations attributed to the war in Ukraine and the increase in interest rates from a very low base. It's estimated that globally, the cost of building offshore wind farms has increased by 30-40%. In Taiwan, the cost increase is compounded due to onerous local content requirements, making Taiwan's project almost twice as expensive to build now as when they were originally conceived.

Contrasting developments: Solar and geothermal energy

Solar energy: Well-understood and quickly de-risked

Unlike with offshore wind, solar projects have much more local participation. Their financing is well understood by the local developers and financial institutions. The corporate structure is similar to offshore wind, with holding companies containing individual projects as SPVs, which are preferred by banks. Most of the local players are connected to real estate developments or are Engineering, Procurement and Construction (EPC) companies.

The business model begins with local agents initiating the project and obtaining the land and all the relevant development permits. Investors are then invited to buy in. The originator might remain with a 10-20% stake in the project. The debt/financing split is usually 20/80 rather than the 30/70 we see in offshore wind, reflecting the further extent to which solar is de-risked and the fact that construction is faster and relatively less complicated.

Solar in Taiwan is still supported by FiTs and will likely remain so for the foreseeable future. The chief bottleneck for projects is obtaining suitable land. Hybrid uses of land such as agrivoltaics (planting crops on solar farms) are encouraged and open up the possibility of projects on land zoned for agriculture.

The revenue stream of solar is much stronger in comparison to the investment scale, with lower interface risk. The largest solar project in Taiwan might be 150MW in size, with construction time of just six to nine months. The risk is highly front-loaded and banks are confident in participating in such projects.

Geothermal: High reward, high uncertainty
Geothermal is a highly attractive source of renewable energy due to its baseload characteristics and has accordingly been given an attractive FiT. But development in Taiwan is still highly preliminary, with multiple uncertainties that might give financiers pause.

Taiwan is lacking in drilling expertise, with only the state-owned CPC possessing any whatsoever. Available locations are often rife with land-use issues as they are often in national parks, on indigenous land, or adjacent to commercial hot-spring operators.

It's critical for the success of the project to "strike heat." Even with heat from a first hole, however, a second one must still be drilled and connected to the first. The project is substantially de-risked after the second hole is successfully connected and becomes attractive to investors. But the high level of uncertainty makes it difficult to find willing investment and financing before that point. Very high levels of equity participation is required to initiate the project.

Even after heat production commences, some uncertainty remains. Heat production might decrease precipitously after a number of years. This could change the rate of return of the project in ways that are impossible to predict at its onset. Project size in Taiwan ranges from one to 10 megawatts, relatively small compared to the size of the initial investment. Funds looking to invest in geothermal globally that can tolerate the risk do exist, but they consider the Taiwanese market too small.

Conclusion

There's been a recent renewal of interest in geothermal in Taiwan, which will require action from the government to capitalize on. Legislative changes to smooth the path to obtaining land and more public support could change the market dynamic and spur development. As highlighted, urgent dialogue is needed between developers and government on green finance over the next year as final investment decisions are made on a large number of projects.

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Taiwan's Offshore Wind Development

Angelica Oung

INTRODUCTION

Since the first onshore wind project was installed in Taiwan in 2020, more than 800MW of onshore wind capacity has been installed across the country. However, Taiwan's initial rapid progress on this energy source has unfortunately stalled. In particular, increasingly thorny land-use disputes caused some projects to be abandoned outright, or halted development. Despite the strong demand for green energy, little further progress is currently expected from onshore wind. However, while Taiwan's small size and the presence of strong NIMBY movements limits onshore wind, offshore wind offers far greater potential. The western side of the island – where the wind blows strongly through the Taiwan Strait offers excellent wind resources, especially in the winter months.

Accordingly, the Taiwanese government has chosen to target offshore wind as a primary source of renewable energy for decarbonization, setting an ambitious goal of 5.7GW installed capacity by 2025, and 15GW by 2035, under the Thousand Wind Turbines Project.

With the election of President Tsai Ing-wen in 2016, the project kicked off in earnest. Tsai's administration sent clear policy signals that Taiwan was serious about its offshore wind ambitions and succeeded in attracting international investment. Such investment has been seeking new markets like Taiwan as a result of the European FiT (Feed-in-Tariff) scheme starting to be wound down. Taiwan instituted generous FiT programs, with some tariffs as high as NT$6.04 per kilowatt hour, guaranteed for 20 years – perhaps the highest in the world at that time.

1. Round 1 ("Demonstration") comprises just two projects totaling 360MW.

2. Round 2 ("Transition") has developers vying for 5.5GW worth of projects on sites pre-selected by the government.

3. Round 3 ("Zonal Development") will run from 2025 to 2030, with a total of 15GW capacity to be awarded over the course of five auctions.

Unlike Round 1 and 2 projects, Round 3 projects will not benefit from generous FiT incentive structures. Instead, developers are expected to sign 20-year Corporate Power Purchase Agreements (CPPAs) to finance their projects. As a result of this structure, Taiwan quickly became the leading offshore wind market in Asia outside of China, far ahead of Japan and South Korea. Construction suffered heavy setbacks during COVID, incurring heavy costs and delays. However what could be more serious is the financial viability of future projects.

In 2023, offshore wind was hit globally with escalating costs due to commodity price gyrations and increased interest rates, which caused a 30% rise in the cost of projects. This affects projects worldwide, but as Taiwan's are already some of the most expensive in the world due to a heavy Local Content Requirement (LCR), the profitability of Round 3 projects are now in question.

Beyond providing Taiwan's tech sector with the renewable energy it needs to satisfy supply chain requirements, offshore wind is also expected to be a substantial source of low-carbon power for Taiwan's grid. However, peak production occurs in winter, which is substantially out of phase with Taiwan's electricity demand, which peaks in the summer.

Finally, one further source of concern is the inherent intermittency of wind as an electricity source. This problem is particularly acute as Taiwan is an isolated grid, and thus cannot shift the surplus (or account for a deficit) by relying on electricity trading with surrounding grids. Currently, with offshore wind accounting for less than 2% of the grid, this is a non-issue, but will become a serious problem as installed capacity increases, especially as solar energy, another intermittent source, grows too.

WHAT WE MUST CONSIDER

The introduction above provides an overview of the current state, proposed development, and potential challenges facing wind power in Taiwan. While these challenges cannot be ignored, wind, at present, has little penetration in Taiwan, and the problems described above only become severe at far higher penetrations.

Thus there exists a substantial well of untapped potential for greater decarbonization through the increased deployment of offshore wind. An examination of similar grids indicates that wind energy can achieve a penetration of approximately 25% (more than ten times the current penetration) before issues of intermittency become severe enough to limit, or even halt, further development.

Wind is a mature technology: modern turbines are efficient, not particularly resource-intensive, and thanks to the scale of manufacture, are cheap to purchase and install, even in a challenging offshore environment. Furthermore, the technology required to integrate wind into a grid effectively is maturing rapidly.

Taken together, this would suggest that Taiwan stands in a position to pursue wind energy and increase its penetration dramatically. While wind is not inherently a complete solution, it can nonetheless become part of the solution, in tandem with other generation methods. Present data indicates that it would be feasible to construct up to 12GW of offshore wind generation capacity with existing technology, at low cost. This marks a more than tenfold increase over present onshore capacity, which is less than 1GW as of 2024.

The option to generate substantial amounts of power from wind offers the chance to reduce the dependency of Taiwan on imported energy. With the volatility observed in global energy markets, particularly since the invasion of Ukraine by Russia in 2022, reducing the exposure of Taiwan to such fluctuations should be a high priority, and wind can contribute greatly to that goal. With that said, other generation sources must be explored and developed in tandem with wind, and due to the isolation of Taiwan's grid, a means of managing wind's intermittent nature (ideally, storing the winter excess through conversion to synthetic fuels, for instance) should be found.

CONCLUSION

Offshore wind is a critically important source of low-carbon power in Taiwan, and the government should prioritize its healthy development. Healthy development means that the approach should, fundamentally, be pragmatic. Taiwan is not likely to create world-class wind component manufacturers through imposing a “local content” policy due to the small size of the market, and doing so could jeopardize future wind farm projects through supply constraints and increased costs.

Keeping with this pragmatic attitude, there also needs to be a measure of realism about how much offshore wind there is in Taiwan. While we are surrounded by the ocean, much of it is already in use as harbor and shipping lanes; for defense purposes; as protected wildlife habitat; or as fishing grounds. These restrictions leave us with 12GW of viable wind projects, before we push off into deep waters (literally and figuratively) that necessitate expensive and lesser-proven technologies such as floating wind technology. The costs of such projects beyond the 12GW barrier are still uncertain.

Lastly, we also need to address the fact that offshore wind is produced mostly in the winter months while Taiwan’s grid peaks in the summer. While offshore production is higher in capacity factor than onshore, it is still highly intermittent. As an isolated grid, offshore wind can be valuable for us, but we must consider that at high grid penetration it will become increasingly difficult for Taiwan to manage.

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Hydrogen opportunity and challenges

Toby Collins

The world is in the early stages of an unprecedented energy transition, in which governments and organizations are trying to change the planet's entire energy infrastructure. They have set a targeted completion date of 2050 for this monumental shift, but it's likely to continue far beyond that.

Whereas for the past century, the world has relied on one or two relatively stable energy sources, we are now moving toward a fragmented system that is adaptive to local conditions but which includes many unknowns. Multiple solutions using new technologies and innovative processes are announced each year.

Among these solutions, hydrogen is becoming more widely accepted and could play a critical role in many different areas. Perhaps the most widely discussed use is in transportation, including long-haul trucks, buses, ships, and planes. There have been heated debates on the pros and cons of pure battery electric vehicles versus hydrogen-powered vehicles, or a hybrid of the two. But like most areas in this energy transition, there is no one clear winner. Each provides opportunities as well as challenges.

Beyond transportation, heavy industrial processes such as steel and iron production can incorporate hydrogen, dramatically reducing carbon emissions. However, this will take time and significant investment, as steel mills will need to be redesigned or rebuilt. Still, we are already seeing positive developments in some leading steel mills in Northern Europe, which are actively promoting hydrogen as the best way to decarbonize.

Energy storage is another area in which hydrogen can be used effectively . Extreme fluctuations in energy production from renewables like wind and solar make it difficult to provide a consistent and stable energy supply. Hydrogen as an energy carrier offers a great way to store excess power when there is an oversupply, and then to release power when demand is too high.

The major issue with hydrogen, however, is where to find it. While hydrogen is the most abundant and lightest element in the universe – estimated at around 70% of the total mass – it is rarely found in its natural state. Unfortunately it is currently very expensive and energy intensive to separate which may appear to contradict its promise as a clean, renewable energy source. There is currently no viable solution that is 100% efficient or cost-effective enough to make hydrogen production more widely accepted. The production methods currently being explored are popularly referred to as green, blue, turquoise, pink and white, among others. These methods are described in the chart below.

Type of Hydrogen	Turquoise	Green	Blue	Yellow	Grey	Pink	White	Black& Brown
Associated Processes	Thermo catalytic Pyrolysis	Electrolysis	Carbon Capture Storage post SMR	Electrolysis with Solar power	SMR - most common without gas capture	Nuclear energy (also referred to as purple, red)	Hydrogen from fracking	Gasification of hydrocarbons
CO2e in process	None	None	Yes	None	Yes	Yes	Yes	Yes

However, each process has some degree of carbon footprint, and the references to colors can therefore be misleading. It is not as simple as just choosing green hydrogen, which can still produce small amounts of carbon. This can change quite dramatically depending on the type of electrolyser used, how and where it is installed, and the purity of the renewable energy supply that it uses. Some technologies like methane pyrolysis (turquoise hydrogen) require 70% less energy than electrolysis and can generate hydrogen with a negative carbon footprint if they use biogas as a feedstock. Furthermore, pyrolysis creates a solid carbon by-product, for which there is growing interest given its value in improving conductivity in batteries or the strength of concrete. The more traditional steam methane reforming (SMR) process can produce blue hydrogen and with the right technology can capture up to 90% of the carbon emissions.

Multiple innovative technologies are being tested for each of these processes and improvements are constantly being made. For electrolysis, alkaline, proton exchange membrane (PEM), solid oxide and, more recently, anion exchange membrane (AEM) solutions are being looked into. Catalytic and plasma technologies are being explored for methane pyrolysis; these can be adjusted based on the environment and customer requirements. These options offer promising solutions for the future.

Geography also plays a significant role in finding the best renewable energy source to make hydrogen. Abundant sunshine and land has given China, India, UAE and the lead on solar projects, and the consistently high winds of the North Sea in Europe are suitable for offshore wind. Taiwan has a possible advantage with geothermal, though as primarily an energy importer, it is likely to focus on natural gas until its offshore wind program reaches maturity. Nuclear, which is constantly being debated as the best and fastest way to reach our net-zero goals, offers another option for producing hydrogen.

Perhaps the greatest challenge that needs to be overcome for hydrogen is the perception of safety. The famous Hindenburg disaster in 1937, in which a German Zeppelin caught fire, killing 35 people, seems to immediately come to mind when considering hydrogen. Or the fact that the hydrogen bomb has a greater destructive power than the first-generation nuclear bombs, doesn’t inspire great confidence for its use as an alternative fuel to diesel. The reality, however, is that hydrogen has no rating for innate hazard, reactivity, or toxicity, and the only by-product from its use as an energy carrier is water. Furthermore, a number of hydrogen’s properties make it safer to handle and use than the fuels commonly used today, including gasoline, natural gas, uranium, jet fuel, and diesel. It dissipates rapidly into the air when released and if ignited somehow, not only will the fire burn out far faster than an oil or gas fire, but it will also burn up and away.

Transporting and distributing hydrogen as a liquid or gas is also challenging and must be done carefully. However, transportation issues are true of every energy carrier used today. Natural gas, oil, gasoline, diesel, and LNG are all challenging to transport and distribute, and come with numerous safety risks (arguably greater than those involved with hydrogen). The practices and safety methods are incredibly well established. Pressurized gasses are used in a vast number of industries and settings, and the world is well versed in safe handling practices with over a century of experience.

Taiwan, compared to other neighboring countries, is in the relatively early stages of hydrogen adoption. However, there are promising signs that it will follow global trends in mobility and low-carbon hydrogen production. Taiwan's first two hydrogen refueling stations will be completed in the third quarter this year, and with that we are likely to see the first hydrogen-powered vehicles come to market in Taiwan.

The global challenge for hydrogen mobility is having enough stations to provide refueling services at multiple locations; however, the threshold for this is lower for Taiwan due to its smaller size. One fully loaded hydrogen truck could theoretically make it from the north to the south of the island, a journey of about 350 km, with just one fill. We are therefore likely to see the adoption of hydrogen in heavy mobility first, where drivers have a fixed daily route. Private passenger vehicle use should follow once sufficient refueling stations are built.

On the low-carbon hydrogen production side, Taiwan has several options in the near term, and it currently has sufficient volumes of blue hydrogen produced from natural gas through SMR and carbon capture. As previously mentioned, utilizing the natural gas supply in Taiwan will be the most obvious choice for the coming years, which suggests that SMR will continue to be the preferred option. Methane pyrolysis, producing turquoise hydrogen and solid carbon, may also be considered but will also require significant investment, and the market for high-grade solid carbon, or nano-carbon, is still uncertain. While there are some electrolysis projects being launched this year to produce green hydrogen, this is still very expensive and as demand grows it will be hard for Taiwan to produce enough locally at the right cost. Like Japan and Singapore, Taiwan may need to look at importing green hydrogen from other places like Australia or the Middle East, where abundant sunshine allows for a much larger production volume.

Globally, numerous challenges must be overcome before hydrogen can live up to its promise of becoming an environmentally friendly wonder fuel. The costs are daunting, the technical progress required huge. But these problems can be solved by investment-driven innovation. To get the ball rolling, governments need to step up, private industry needs to be incentivized to take on more risk, and everyone needs to work together to make a cleaner, brighter future for future generations.

Toby Collins- Managing Director of Lien Hwa New Energy
Toby Collins is an entrepreneurial business leader from the UK. He established HwaQi, a company dedicated to energy efficiency within the semiconductor industry. In 2023, Toby helped create Lien Hwa New Energy, a new business unit within the Mitac-Synnex group.
Toby is currently the managing director of Lien Hwa New Energy and sits on the Board for Asia Hydrogen Energy and HwaQi.

Taiwan's NDC Plan and Carbon Dioxide Removal

Tank Chen

Overview of Taiwan's NDC plan

Taiwan's Nationally Determined Contribution plan (NDC) is the framework for its approach to addressing climate change and contributing to global efforts towards sustainability. Originating from its initial commitment in 2015, Taiwan's NDC set an ambitious target of a 20% reduction in its net emissions from 2005 levels by 2030. In a recent update, this target has been revised to an enhanced reduction goal of 23-25% by 2030, aligning with the principles of the Paris Agreement, which emphasizes common but differentiated responsibilities. This revision reflects Taiwan's commitment to not only meet but to exceed its previous emissions reduction targets, laying a solid foundation for achieving net-zero emissions by 2050.

In March 2022, Taiwan introduced the Pathway to Net-Zero Emissions in 2050 roadmap (hereinafter, the Roadmap), a comprehensive plan outlining a trajectory and action path toward the country's net-zero goals. The Roadmap underscores the importance of promoting technology, research, and innovation across key sectors, guiding a green transition for industries, stimulating economic growth, and enhancing green financing and investment. These efforts are geared toward ensuring a fair and smooth transition to a sustainable future.

Major strategies and foundations

The pathway Taiwan has set for itself is structured around four major transition strategies: energy, industrial, lifestyle, and social transitions. These strategies are supported by two critical governance foundations: technology R&D and climate legislation. To bring these ambitious goals to fruition, Taiwan has identified "12 key strategies" encompassing action plans for expected growth areas in energy, industry, and lifestyle changes necessary for a net-zero transition.

The Roadmap

At the heart of Taiwan's climate action plan is the dual objective of environmental sustainability and competitiveness. The Roadmap aims to catalyze economic growth, attract private investment, create green jobs, achieve energy independence, and enhance social welfare. The government has pledged to establish competitive, sustainable, resilient, and secure governance foundations and transition strategies to support these goals.

12 key strategies

The plan's 12 pivotal areas for action address net-zero energy, industrial, and lifestyle transitions. These include the development and deployment of wind and solar photovoltaic power, hydrogen energy, innovative energy solutions, power systems and energy storage technologies, and measures for energy saving and efficiency. Also critical to the strategy are Carbon Capture, Utilization, and Storage (CCUS), the promotion of carbon-free and electric vehicles, resource recycling toward zero waste, the establishment of carbon sinks, fostering a green lifestyle, enabling green finance, and ensuring a just transition for all sectors of society.

Role of Carbon Capture, Utilization, and Storage, and carbon dioxide removal in the NDC plan

The NDC incorporates carbon dioxide removal (CDR) strategies as a pivotal component of its comprehensive approach to achieving net-zero emissions by 2050. The plan recognizes the critical role of CDR in addressing emissions from sectors that are challenging to decarbonize and outlines specific strategies for leveraging both technological and natural solutions to enhance carbon sequestration.

Residual emissions and CDR targets

By 2050, Taiwan aims to reduce its residual emissions from hard-to-abate sectors to 22.5 metric megatons of CO2 equivalent (CO2e). This reduction will be balanced with an equal capacity of carbon sinks in forestry, soil, and marine ecosystems. Additionally, the plan outlines the necessity of carbon capture, utilization, and storage (CCUS) technologies to avoid 44.5 metric megatons of emissions, ensuring the nation stays on course to meet its

Role of CCUS

The NDC plan gives priority to the development and implementation of CCUS technologies, focusing on capturing carbon emissions from industrial and energy facilities. A significant emphasis is placed on carbon capture and utilization (CCU) technologies that can transform captured CO2 into chemical raw materials and building materials, creating a carbon cycle value chain. Taiwan is also exploring the potential for carbon storage sites and implementing a safety verification site program to support this endeavor.

Not explicitly mentioned in the action plans, but included in the broader strategy, are Direct Air Capture (DAC) and Bio-energy with Carbon Capture and Storage (BECCS). These technologies are considered crucial for removing atmospheric CO2. The strategy highlights the prioritization of microalgae-based direct air carbon capture and the use of solid sorbents and biomass in the short term, with plans to scale up these technologies by 2040-2050.

Execution strategies encompass both technical and geological aspects, with the National Science and Technology Council (NSTC) leading the technology development and geological exploration. The NSTC's efforts are supported by the Ministry of Economic Affairs (MOEA), which focuses on industrial applications.

Carbon sink strategies

To further reduce atmospheric CO2 concentrations, Taiwan is implementing afforestation and management measures, establishing carbon-negative farming methods, and enhancing marine habitats. The National Greenhouse Gas Inventory Report highlights that the forestry sector alone removes over 22 million metric tons of CO2 annually, accounting for approximately 7.6% of the country's total emissions in 2021.

The action plans for increasing carbon sinks focus on developing and enhancing carbon sequestration in forests, soils, and marine environments. Strategies include:

1. **For forests:** Increasing forest coverage, enhancing forest management, and utilizing domestic timber to maximize carbon sequestration.

2. **For soil:** Improving soil management and promoting carbon-negative farming approaches to enhance soil carbon sequestration.

3. **For marine environments:** Developing methodologies for monitoring, reporting, and verification (MRV) of carbon sequestration, managing wetlands, and restoring aquatic plants to significantly increase marine carbon sinks.

By 2030, Taiwan aims to significantly increase its carbon sequestration capacity through these measures, with targets for marine carbon sequestration at 340,000 metric tons of CO2e, forest carbon sequestration at 758,000 metric tons of CO2e, and soil carbon sequestration at 259,500 metric tons of CO2e, for the combined goal to sequester 1,4 metric megatons of CO2e by 2030 through these carbon sequestration efforts.

Although the NDC plan does not specifically outline novel CDR methods beyond those mentioned, it suggests an openness to exploring new technologies to enhance marine carbon sinks and incorporating practices such as biochar application in carbon-negative farming. This suggests an openness to adopting additional innovative carbon removal technologies to achieve its net-zero ambitions.

Current status of CDR in Taiwan

Beyond the development of carbon capture technologies and enhancement of natural carbon sinks, a notable CDR initiative in Taiwan involves the application of agricultural waste-derived biochar in croplands to improve soil health and sequester carbon.

Biochar application in Taiwan

Biochar is produced through the pyrolysis of biomass, such as crop residues, in environments with controlled temperature and oxygen levels. This process can occur on various scales, from small, on-site units at individual farms to larger, centralized facilities.

Research and academic studies have extensively documented the conversion of agricultural residues to biochar. Estimates by the Ministry of Agriculture indicate that Taiwan generates between 4.6 to 5.19 million metric tons of agricultural waste annually, 42% of which comes from produce that is often disposed of inefficiently—either buried or burned on-site—leading to pollution and greenhouse gas emissions.

Research shows that there are around 300,000 hectares of highly acidic soil in farmlands in Taiwan, which is particularly suitable for biochar application. Calculations suggest that up to 12 million metric tons of biochar could be applied to these lands, assuming a 2% organic carbon content integration into the 0-20 cm topsoil layer. If annual production can reach 200,000 metric tons, this would allow for the treatment of 1 metric megaton of agricultural waste, enabling biochar application to acidic soils for up to 50 years. This approach promises to improve soil properties and enhance soil carbon sequestration capabilities significantly, in addition to removing carbon and the conversion of plant biomass to biochar.

Challenges and opportunities

Despite the clear benefits and potential of biochar, several challenges impede its widespread implementation. Key issues include the absence of a designated governing body for biochar policy and the lack of clear regulations concerning its production and use. Currently, Taiwan does not have a developed biochar industry. Its production is limited by the availability of equipment and facilities, and the distributed nature of biomass feedstocks complicates collection for industrial-scale pyrolysis. The absence of policy and financial support further hinders the economic viability of locally produced biochar from smaller, artisan projects.

Recognizing these challenges, the government established the Biochar Specifications, Grading, and Safety Standards in 2019, referencing international standards. The initiative aims to promote a certification system, establish a biochar label, and strengthen the industry chain. The development of methodologies concerning the materials' source and nature, pyrolysis operations, and biochar usage is currently underway. However, real-world deployment of biochar in croplands has not yet begun.

4. Feasibility and realism of NDC's reliance on CDR

Taiwan's NDC plan seems to suggest it is following a dual-target strategy: reducing emissions and compensating for residual emissions through CDR. The reliance on CCUS and natural carbon sinks (forest, soil, and marine systems), however, present several challenges that could impact the feasibility and realism of the plan's goals.

Challenges with CCUS

First, CCUS technologies are expensive, and Taiwan lacks the necessary infrastructure and storage sites for carbon. Second, there's a lack of relevant regulations and standards for CCUS implementation. Third, technologies for exploration, engineering, and the methods of monitoring and maintaining CCUS facilities are still in the early stages of development. And lastly, there is a potential shortage of skilled workers to build, operate, and maintain CCUS technologies. To address these challenges, government agencies advocate for continuous subsidizing of R&D in forward-looking technologies, improvement of existing technologies through industry collaboration, and the promotion of demonstration projects. Collaborating with academic institutions for long-term monitoring, safety assessments, and prioritizing the development of technologies for regional geological and marine information are also crucial steps.

Enhancing natural carbon sinks

Natural carbon sinks also face several limitations. Available land for new tree growth is scarce, limiting the expansion of forest sinks. Natural sinks are also increasingly vulnerable to climate change, which affects their carbon sequestration capacity. More importantly, carbon stored in forests and soils is less durable compared to geological storage, posing risks of release back into the atmosphere. Addressing these challenges requires setting regulations and standards, developing methodologies, and creating incentives for conservation management to ensure the sustainability and effectiveness of natural carbon sinks.

Future directions

The actual need for CCUS by 2050 will depend on Taiwan's future energy structure. Nonetheless, achieving net-zero will require removing millions of metric tons of CO2, pointing to the need to both optimize existing CDR methods and explore novel, more durable carbon removal technologies. Doing so will require a balanced mix of technological innovation, regulatory support, and international cooperation.

Taiwan's Nuclear Development

Alexander G. Kaufman

In 1985, Taiwan had one of the cleanest power grids in the world. It didn't really matter then, with roughly 25% fewer carbon dioxide particles circulating in the atmosphere than today. Rather, the three nuclear power plants generating more than half the island's electricity were valued for their steady output of cheap power to sustain Taiwan's "economic miracle."

A year later came the meltdown at the Soviet nuclear plant in Chernobyl of an experimental reactor with none of the modern infrastructure to contain an accident. The disaster spread radioactive isotopes across part of Eastern Europe.

That same year, pro-democracy activists in Taiwan formed the movement that would ultimately become the Democratic Progressive Party (DPP), which vowed to end the authoritarian Kuomintang (KMT) regime's expansion of nuclear power. Following Taiwan's transition to liberal democracy in the 1990s, the DPP and the KMT became the dominant political parties, primarily distinguished by the former's preference to maintain the island's de facto independence and the latter's determination to eventually unify with China. The DPP's traditional anti-nuclear stance hardened again amid the global panic over the 2011 meltdown in Fukushima, Japan.

In 2014, anti-nuclear campaigners successfully pressured the ruling KMT administration at the time to halt construction on Taiwan's fourth and most technologically advanced atomic energy station. Tsai Ing-wen of the DPP won the following presidential election in 2016. Soon after taking office, she established a "nuclear-free homeland policy," which would see all of Taiwan's three operating nuclear plants by 2025.

At the Jinshan nuclear power plant, the country’s debut facility located on the northern shore of New Taipei City, the first reactor closed in 2018 and the second was shuttered the following year. Guosheng nuclear power plant, Taiwan’s No. 2 facility, is located around 20 minutes southeast along the coast from Jinshan. It permanently powered down its first reactor in 2021, followed by its second in March 2023.

The only two remaining reactors are located at Taiwan’s opposite end, in southernmost Pingtung county, at the Maanshan nuclear power plant. The first reactor’s operating license expires on July 26, with the second unit slated for decommissioning on May 17, 2025.

The Tsai government had initially pursued a more aggressive timeline, but attempted closures of reactors in 2017 caused electricity shortages. The administration fell short of its targets for offshore wind turbines, the energy source expected to provide an alternative to zero-carbon power lost when the nuclear reactors shuttered. Despite touting its plans to reach net-zero emissions by 2050, Taiwan – which consistently ranks among the world’s top 25 biggest emitters of carbon dioxide pollution – expanded its coal fleet and undertook a large-scale buildout of gas-fired power plants and infrastructure to import liquefied natural gas.

Not only did this dependence on natural gas make Taiwan vulnerable to the fuel’s volatile price swings.but Taiwan’s storage facilities for natural gas contained less than a month’s worth of fuel, which – absent connections to any pipeline networks – must be imported by ship and replenished almost constantly. Coal, in contrast, can be stockpiled for months, while nuclear reactors can go years without refueling.

Russia’s February 2022 invasion of Ukraine highlighted the unique geopolitical risk of depending on natural gas for heating and electricity as European democracies scrambled for alternatives to the cheap fuel Germany, France and Italy purchased from Moscow via pipelines. That August, the Chinese military’s missile tests around the Taiwan Strait following the former U.S. House Speaker Nancy Pelosi’s controversial visit to Taipei instituted what seemed like an unofficial blockade, scattering LNG barges destined to Taiwan’s ports.

The benefits of nuclear reactors to withstanding Beijing’s military attempts to impose on Taiwan’s sovereignty are widely recognized by energy security experts. Even in a feared amphibious invasion, China would be unlikely to attack facilities that risked irradiating its nearby and heavily populated coast. If China instead sought to cut Taiwan off from the outside world, the island’s fully fueled reactors could produce steady electricity for two years or more. It is an irony of Taiwan’s democracy that the party bent on prolonging the island’s autonomy is the one dedicated to eliminating its domestic nuclear industry.

Incoming President Lai Ching-te won election in January promising to continue Tsai’s skeptical approach to dealing with an increasingly aggressive China. As the sitting vice president, Lai is still tasked with implementing Tsai’s agenda. But he also suggested during his campaign that nuclear reactors could offer benefits in emergencies.

Lai will also rule over a divided government. Despite his presidential victory, the DPP lost its control in the Legislative Yuan, where the KMT is now the largest party with the ability to command a majority in votes through a loose alliance with the upstart Taiwan People’s Party, the third-largest party.

Taiwan’s state-owned monopoly utility, Taipower, is also facing potential shortages again. The island avoided major outages last year despite Guosheng’s closure in part due to sluggish economic growth of just 1.3%.

On track for nearly triple that growth rate in 2024, Taipower is already urging factories to cut back on electricity usage and shift production schedules to off-peak hours, frustrating manufacturers who are now pressing for more control over their own electrical generation and considering alternative locations overseas.

All of this increases the chances Lai looks to at least partially reverse Tsai’s phaseout policy. The following explains what that process may entail:

1

Saving Maanshan

The Maanshan nuclear power plant was Taiwan's third atomic generating station and the first located outside the Greater Taipei area on the populous northern part of the island. Situated onTaiwan's southernmost peninsula in Pingtung County, the plant's two reactors are the only commercial nuclear generators in operation today. The plant provides as much as 10% of Taiwan's electricity. Its first unit's permit is scheduled to expire June 27, 2024, with the second unit closing May 17, 2025.

Construction began in 1979 on two WE312 pressurized water reactors (PWRs) at Maanshan, the first such facilities in Taiwan's fleet. Unlike the boiling water reactors (BWRs), PWRs add an extra step between the fission reaction's heat and the steam used to generate electricity. PWRs make up roughly two thirds of the U.S. fleet, with BWRs comprising the rest. China's expanding fleet of reactors is primarily made up of PWRs.

While the United States is currently considering new reactors, the country is working to relicense existing plants to extend the lives of these zero-carbon assets. The highest-profile current example is the Pacific Gas & Electric's Diablo Canyon Power Plant in California. The power station's two units were slated to close in 2024 and 2025. Now, with a loan from the Biden administration totaling $1.1 billion, the utility plans to relicense the reactor for at least another five years.

2

Completing Lungmen

The Lungmen Nuclear Power Plant in New Taipei City was slated to be Taiwan's first advanced atomic power station, with a new-century reactor model designed with passive safety features. The General Electric Advanced Boiling Water Reactor had already been deployed in Japan and licensed in the U.S. But the project was halted amid protests under former KMT President Ma Ying-jeou and mothballed when President Tsai took office.

The U.S. offers another example of a reactor whose construction began years, even decades, before completion. The most recent reactor to go critical in the U.S. prior to the two new reactors at the Alvin W. Vogtle Electric Generating Plant in the southern state of Georgia was the Watts Bar Unit 2 reactor of the Tennessee Valley Authority. The project began in 1973, was halted in 1985, resumed in 2007 and completed in 2016.

3

Reopening closed reactors

While Taiwan has already shuttered two nuclear plants, the U.S. again offers an example of reversing course. In March, the Biden administration offered the decommissioning company Holtec International US$1.5 billion to reopen the Palisades Nuclear Generating Station in Michigan, the most recently shuttered atomic station.

Holtec said it plans to use the money to relicense and restart the single reactor. If successful, the company has indicated it would expand the facility with additional small modular reactors (SMRs) of its own design.

4 Expanding existing facilities

All of Taiwan’s nuclear power plants were built with additional space designed for more reactors. Experts have said this would make it possible for Taiwan to restore and increase its nuclear-generating capacity without siting new full-scale power plants on greenfield locations.

5 New build debate: Big reactors vs. SMRs

Taiwan’s growing need for electricity suggests the country could benefit from the gigawatt-scale electricity production that the large light water reactors that make up the existing fleet provide. Virtually every commercial reactor under construction now is a light water reactor. In the U.S. and Europe, however, companies are competing to commercialize SMRs.

These are premised on the idea that, like solar panels and wind turbines, nuclear reactors can benefit from assembly-line repetition and get cheaper with each identically built reactor. Skeptics warn that key attributes of SMR power plants will still need to be built on site, and that the reduced output of power from the machines makes their economic advantages of large-scale reactors hazy at best. Currently in the U.S., researchers estimate that the cheapest next reactor to build will be a large-scale Westinghouse AP-1000. The long-awaited completion of two such machines at Georgia’s Plant Vogtle has established the design, workforce and supply chain.

SMRs include a wide range of reactor designs, which can be broken down here into three main categories: small light water reactors, advanced reactors, and microreactors. While the first two categories are exclusive and define the type of cooling system used by the machine, a microreactor is generally anything able to produce 20 megawatts of thermal energy or less.

Small light water reactors include: Westinghouse’s AP-300, GE-Hitatchi’s BWRX-300, Holtec’s SMR-300, Nuscale’s VOYGR SMR, and Rolls Royce SMR.

Advanced reactors include: TerraPower’s Natrium design, X-energy’s Xe-100, Kairos Power’s KP-FHR, and BWXT’s BWRX-300.

Microreactors include: Oklo Inc.’s reactor, Last Energy’s PWR-20, Westinghouse’s eVinci, Ultra Safe Nuclear’s Micro Modular Reactor.

While the SMR race has brought a bevy of new reactor designs into the mix, the companies involved are also experimenting with a range of different business models.

U.S.-based Last Energy is designing not only a stripped down, tiny reactor but a whole modular power plant system with the aim of selling its full product suite to industrial companies looking for an on-site source of nuclear electricity or heat. Oklo, headquartered in the U.S. state of California, aims to own and operate its own power plants and sell electricity as a service either to grid operators or corporate buyers, and ultimately close its fuel supply chain by recycling its waste. X-energy, based near Washington, D.C., is seeking to produce and sell a rare type of fuel in addition to its reactor business.

2

Nuclear-power semiconductors?

Faced with an electricity supply crunch that has recently compelled Taiwan's government to pay factories to reduce output to ease strain on the grid, semiconductor manufacturers – among the largest power users in Taiwan – have grown more bullish on deploying SMRs at their facilities.

This represents a potentially attractive market for SMR companies like Last Energy or Westinghouse to deploy microreactors on site at factories with an agreement to take fuel back at the end of the uranium's operating life. Doing so would reduce the added burden on Taiwan's waste-storage facilities.

On-site SMRs pose a legal challenge in Taiwan. While Taiwan has in recent years amended its Electricity Act to allow for more private ownership of renewables, the statute gives the state a monopoly on operating nuclear power plants. As of April 2024, efforts to propose changes to the Act to allow for the private operation of nuclear reactors are currently underway with opposition lawmakers from the KMT and the TPP parties leading the charge.

4

What about waste?

Among the most common reasons for opposing nuclear power is the concern that there's nowhere to put waste that remains toxic and radioactive for millennia. Like the U.S., Taiwan currently stores the bulk of its most dangerous waste on-site at the power plants where it was produced. Some low-level radioactive waste was transported to and stored on Taiwan’s Orchid Island – or Lanyu – starting in the 1980s, news of which erupted in a scandal that highlighted the long history of oppression of Taiwan’s Indigenous population, who make up 2% of the population. The Indigenous Tao people who live on Lanyu maintain one of the strongest and most distinct cultural identities of any of Taiwan’s 16 recognized Indigenous groups.

Their resistance to new shipments of low-level waste from mainland Taiwan galvanized the pro-democracy movement that ended one-party rule on the island by the end of the last century. For Taiwanese opposed to the authoritarian KMT regime and its long-term focus on reunifying Taiwan with mainland China, the Indigenous struggle served as a poetic symbol of the island’s independent spirit even under earlier periods of mainland rule. For the majority of Taiwanese whose families came to the island well before the 20th century but were still nevertheless ethnically Han, the island’s Indigenous inhabitants offered a more poignant example of difference from the regime in Taipei dominated by mainlanders who came after 1949 and their descendants. Born out of the pro-democracy movement of the mid 1980s, the Democratic Progressive Party positioned itself as a defender of Indigenous people and a fierce opponent of nuclear power.

Ironically, the population of Lanyu – still mostly Tao people, many still living in traditional homes, maintaining sacred fishing rites, and farming taro – remains a loyal voting district for the KMT. Local opinion on the island is mixed. Some Tao people remember the struggle, remain committed to closing the waste storage facility still operating there, and attribute a wide range of illnesses to radiation, even though official statistics show a steady or decreasing cancer rate since the storage facility’s establishment. Others are grateful for the above-average wages workers at the storage site earn and see the facility as a lifeline in a far flung corner of Taiwan where the economy depends heavily on tourism.

In Finland, Sweden, France and the United States, governments have looked to build deep repositories underground to permanently entomb radioactive waste for millennia to come. The first such facility, Finland’s ONKALO, is nearing completion. The U.S. plan at Yucca Mountain in Nevada was scuttled due to political reasons and anti-nuclear opposition. The debate over how to handle spent uranium fuel is stymied in the U.S. by a law that made the federal government the sole final steward of radioactive waste. That same law designated Yucca Mountain as the exclusive first site for a permanent repository. With the project permanently stalled, Congress needs to change the law to allow federal regulators to consider alternative locations.

Private companies in the nuclear space are looking to revive waste management solutions. Holtec International – long the U.S. leader in near-term waste storage equipment and plant decommissioning – is pushing forward with an intermediate-term storage facility in New Mexico.

Canada's Deep GEO is working on establishing deep-burial storage and has already signed agreements with African countries considering their first nuclear plants.

Startups such as Curio LV and Shine Technologies are in the early stages of working with federal regulators to build the first U.S. facility for recycling nuclear waste. Japan, Russia, France and the United Kingdom already recycle waste. But the U.S. canceled its debut waste recycling facility in the 1970s out of fear that the project posed too great a risk to nonproliferation efforts, since the technology for reprocessing spent fuel mirrors what's needed to extract material like plutonium for weapons.

The availability of waste-recycling technology is largely irrelevant for Taiwan. Taiwan is barred under a treaty with the United States from recycling its waste, a legacy of Washington's efforts to thwart Taipei's attempts to develop an atomic weapon in the 20th century. Under its "gold standard" 123 Agreement, Washington has full oversight over Taiwan's nuclear fuel cycle. South Korea has a similar agreement with the U.S., but not as strict. Officials in Seoul have recently pushed for the right to reprocess nuclear waste. In another sign of growing interest in the region, the Philippine Nuclear Research Institute this year signed a deal to work with the U.S.-based Curio.

Expand dry storage

Taiwan's government justified its closure of nuclear plants in part on the loss of additional space to keep spent fuel rods. But all of the storage pools at Taiwan's nuclear plants are full or near full, posing a threat if an earthquake or another disaster damages a facility containing such concentrated radiation.

In the runup to Taiwan's national elections last year, Hou Yu-ih, the incumbent mayor of New Taipei City and the KMT's candidate for president, pledged to give prompt local permitting approval to plans to expand the storage infrastructure at the Jinshan Nuclear Power Plant. As of April, the Tsai administration had yet to resubmit its proposal to build a facility at the defunct station that could handle so-called dry-cask storage containers that have kept waste safe for decades at U.S. plants.

Alexander C. Kaufman is an award-winning reporter and writer and one of the United States' leading journalists regularly covering nuclear power at home and abroad. From his home in New York City, he has traveled across Asia, Europe and Latin America writing about atomic energy. In November 2022, he visited Taiwan to report on the island's nuclear phaseout. Last year, he published a nearly 10,000-word feature article on the history and future of Taiwan's atomic power ambitions. He continues to research and cover Taiwan as a regular part of his beat writing for an international audience of millions of readers. He seeks in this report to provide an outsider's independent, impartial overview through the lens of journalistic analysis the state of nuclear power in Taiwan.

Ocean Thermal Energy Conversion (OTEC) For Taiwan

Alexander G. Kaufman

1 INTRODUCTION / BACKGROUND

What is Ocean Thermal Energy Conversion (OTEC)?

In the tropical oceans sunlight warms the surface layer to more than 25°C, depending on location (see Figure 1-1). This causes a boundary between the less dense warm water and the colder, denser, deeper ocean water. This oceanographic effect is termed the

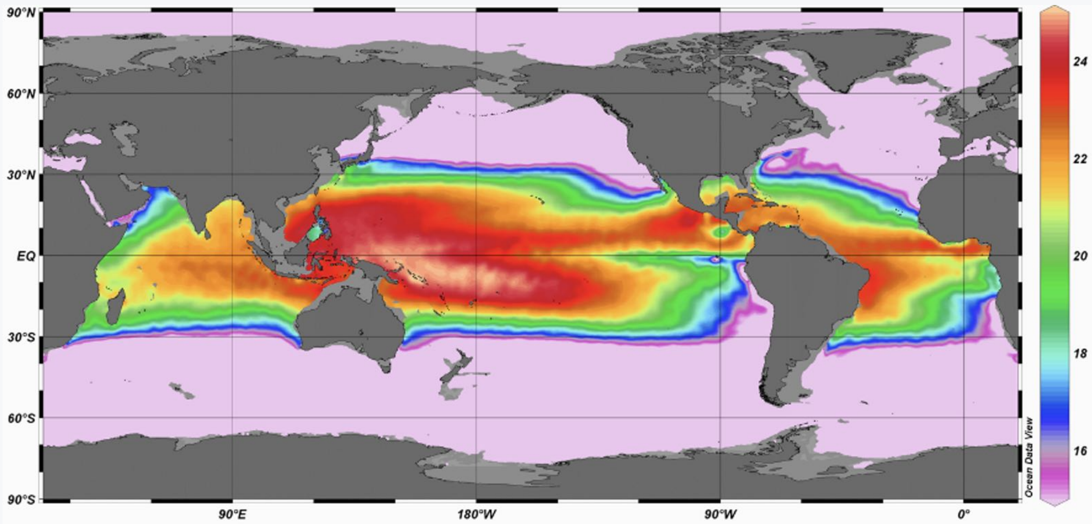


Figure 1-1: Mean annual temperature difference between the typical OTEC depths of 20 and 1,000m, see coloured temperature key on right hand side.

Ocean Thermal Energy Conversion (OTEC) uses these temperature differences to produce electricity. Warm sea water causes a low boiling point liquid such as ammonia to vaporise, which drives a turbine to generate electricity with the vapor condensed by cold deep ocean water (DOW) in another heat exchanger. OTEC can be land based if cold deep sea-water can be found in relatively close proximity to the coast. Floating OTEC is the alternative for the vast area of tropical ocean which is further from land (see Figure 1-3).

Figure 1-2 – Illustration of the Thermocline and Land Band Closed Cycle (CC) OTEC, courtesy of OESL

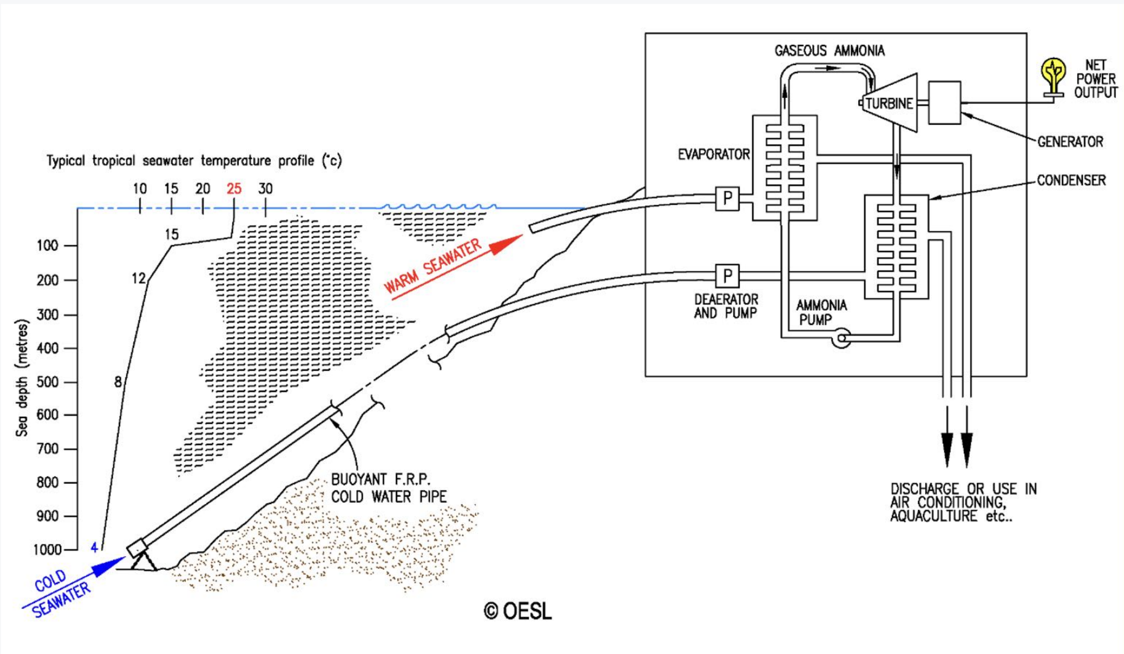
OTEC provides a stable renewable energy source with a power output that does not fluctuate between day and night due to the high specific heat capacity of seawater. Seasonal temperature fluctuations can be predicted in advance and power output sized appropriately.

Since the ocean comprises around 70% of the earth's surface it is a vast receiver and repository of solar energy (see Figure 1-1). While waves, winds, tides and currents are all forms of ocean renewable energy, they suffer from intermittent availability. Significantly, an OTEC system permits the generation of constant 24/7, 365 days-a-year baseload electricity.

OTEC is a proven process which has been demonstrated both on land and at sea. Land-based units have operated successfully for more than 10 years.

As well as low temperature, DOW is also characterized by cleanliness and abundant nutrients, which can be used for aquaculture projects or low-cost air conditioning (see section 2.6).

In summary, OTEC provides the key to accessing the world's huge ocean solar energy storage to allow production of electrical energy and, if required, fresh water.



Taiwan's OTEC potential

Taiwan is incredibly well placed among industrialized nations to have ready access to DOW on its mainland east coast. This can be seen in Figure 1-5 and Figure 1-5. The Tropic of Cancer (23.5° N) runs across the middle of Taiwan.

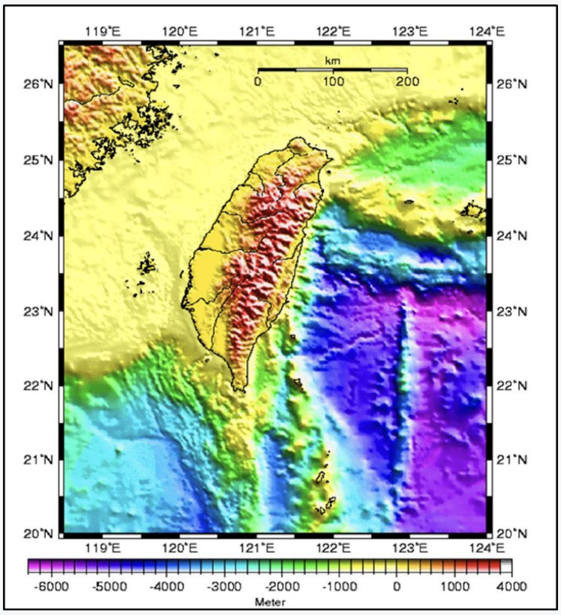


Figure 1-4 – Topographical layout of Taiwan showing deep water on the east coast

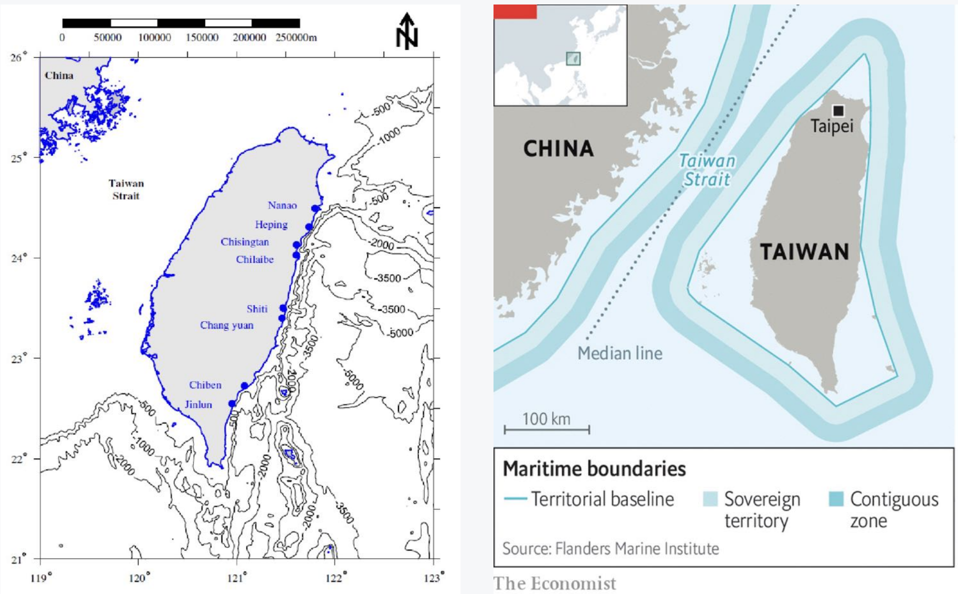


Figure 1-5: Potential coastal sites for OTEC on the east coast of Taiwan, water depth contours are shown in meters plus Taiwan's contiguous zone

It was estimated that the eight potential sites shown in Figure 1-5 have an OTEC potential of 3.2GW see ref (5).
As well as numerous potential land-based sites for OTEC, Taiwan also has a large exclusive economic zone (EEZ) where larger, floating, offshore OTEC facilities could be located. The overall OTEC potential for Taiwan has been estimated to be a gigantic 52GWe of net power within 30km of Taiwan's east coast (Taipower, 1992), see Ref (6).

The benefits of OTEC

OTEC is a benign electricity generation process with no noxious by-products. The main benefits are:

1. **No fuel consumption**
2. **No emission of conventional air pollutants and particulates**
3. **No solid wastes**
4. **Post OTEC plant seawater is virtually identical to ambient water**
5. **Negligible CO_2 emissionsmuch less than with any fossil fuel.**
6. **Complies with the UN's Sustainable Development Goals (SDGs).**
7. **OTEC electricity is stable and not vulnerable to external factors such as changes in oil and gas prices.**
8. **Very high availability factor, probably in excess of 90%**
9. **The public tends to be receptive to the idea, once the basic principle is understood.**
10. **Requires significant capital, but very low operations and maintenance (O&M) costs – simple technology.**
11. **Catastrophic failure (thermal fluid escape) has only local effects, not rising to the level of a major disaster. Ammonia is managed daily in many cold storage facilities around the world.**
12. **Upwelling effect of bringing nutrient nutrient-rich deep water to the surface can enhance biological productivity**
13. **Provides high-quality jobs during design, construction, and operation.**

Figure 1-7 compares OTEC versus other sources of energy both conventional and other renewable sources.

Competitive Issue	OTEC	Nuclear	Coal, Oil & Gas	Wind & Solar	Wave	Current
Source of Fuel	Local renewable	Often Imported internationally-restricted trade	Mostly Imported in our target markets	Local renewable	Local renewable	Local renewable
Is Fuel Accessible?	Yes	Not always country-specific Internationally-restricted trade	Not always requires considerable port & storage areas in target market	Yes	Not always dependent on wave density and frequency	Not always site dependent
Predictable Energy Supply	Yes base load power	Yes base load power	Yes base load power	No unpredictable and usually much lower at night	No	Yes usually predictable
Meeting Load Profile	Constant generation	Constant generation	Constant generation	Unpredictable source	Unpredictable source	Constant generation
Land Required	Small area	Buffer zone required	Fuel handling and storage	Large amounts of real estate	Must be underwater	Must be underwater
Affected by Typical Weather	No unlikely to be affected	No unlikely to be affected	No unlikely to be affected	Yes weather changes cause power output to vary	Yes weather changes cause power output to vary	Yes weather changes cause power output to vary
Affected by Tropical Storms/Hurricaines	No buried pipelines and equipment	No protected equipment usually unaffected	Yes shipping, storage and port facilities vulnerable	Yes structures usually exposed and vulnerable	Yes structures very exposed and vulnerable	Yes structures very exposed and vulnerable
Emmissions/Waste	No Fuel	Problematic waste	High level of pollution	No Fuel	No Fuel	No Fuel

Figure 1-7: Summary of OTEC versus other sources of energy. Courtesy of Ocean Thermal Corporation.

Taiwan's previous work on OTEC

Taiwan has a proud history of supporting worldwide OTEC research. In 1989, the International OTEC Association (IOA) was formed in Taipei (see Figure 1-7). Dr. C. Y. Li, Advisor to the Taiwanese Prime Minister was instrumental in setting up the IOA and arranging government financing for the organisation.

Figure 1-8: Planning meeting of the International OTEC Association (IOA) in Taipei in 1989.

From Taiwan's previous OTEC work, there is clearly a good year-round "delta T" (surface-deep ocean temperature difference) accessible within relatively short distances from the east coast. Also, Taiwan has a high demand for electricity with a need for more power in summer when air conditioning use increases. Fortunately, since Taiwan is in the Northern Hemisphere, power output from an OTEC plant will be somewhat higher in the summer, when the surface water temperatures are higher.

Other past findings for OTEC in Taiwan are as follows:

- **There is no discernible difference in annual average 1,000m-deep ocean temperature between sites – always noted as 4.1°C.**
- **The annual average surface and near-surface temperatures have a slightly increasing trend moving south through the sites. Temperatures are typically around 26°C.**
- **Extreme currents and winds have a slightly increasing trend moving south through the sites. Currents around the islands are generally attributable to the Kuroshio current which flows northward, typically at 1-1.5m/s.**
- **Magnitude of seismic events tends to decrease moving south through the sites.**
- **Possibility to utilize offshore construction experience and port upgrades associated with offshore wind developments.**
- **Opportunity for environmentally sustainable development of Taiwan's underdeveloped east coast.**

2 STATUS OF THE TECHNOLOGY

Existing deep-water pipeline around Taiwan and the rest of the world

Figure 1-7 shows on a world view the 38 sites and 45 deep water pipes that have been installed to date.

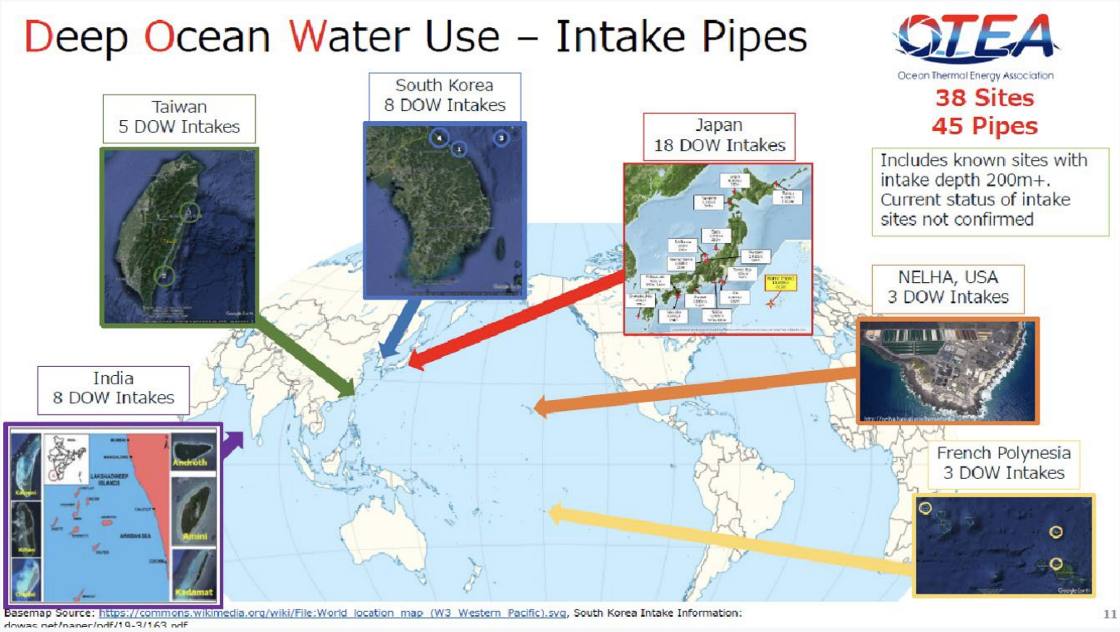


Figure 2-1: Summary of DOW intake around the world. Courtesy of OTEA.

Location-specific challenges for installing deep-water pipeline around Taiwan

Taiwan has frequent typhoons during July to November and a northeast monsoon during October to March. This can impact the time of year when pipeline installation work can be carried out. Taiwan also sits on the rim of the Eurasian plate, which results in frequent earthquakes. Clearly both the possibility of typhoons and earthquakes makes the design of deep-water pipelines more challenging. However, these challenges are not unique to Taiwan and have been successfully addressed at other sites around the world. In addition, engineering analysis tools and earthquake engineering have advanced significantly over the last 15 or so years.

Short History of OTEC

Figure 2-1 summarises the history of OTEC over the last 140 years. It is apparent that considerable progress has been made in this time with a number of successful land-based and floating OTEC systems deployed.

The most relevant of these projects are discussed in more detail in subsequent sections. The work reported in this report mainly concentrates on land based OTEC for Taiwan, since this is likely to be the short to medium term priority. Floating OTEC will eventually be needed for Taiwan to benefit from the full potential of the ocean thermal resource surrounding the island.

Okinawa OTEC demonstration test facility on Kumejima Island

Kumejima Island is located northeast of Taiwan, close to Okinawa Island. It is part of the Ryukyu island chain. Since 2013 an OTEC test facility has been operational on Kumejima (see Figure 2-5). Flight distance from Taipei to Naha on Okinawa is only 354 nautical miles, and flights there take a little more than an hour.

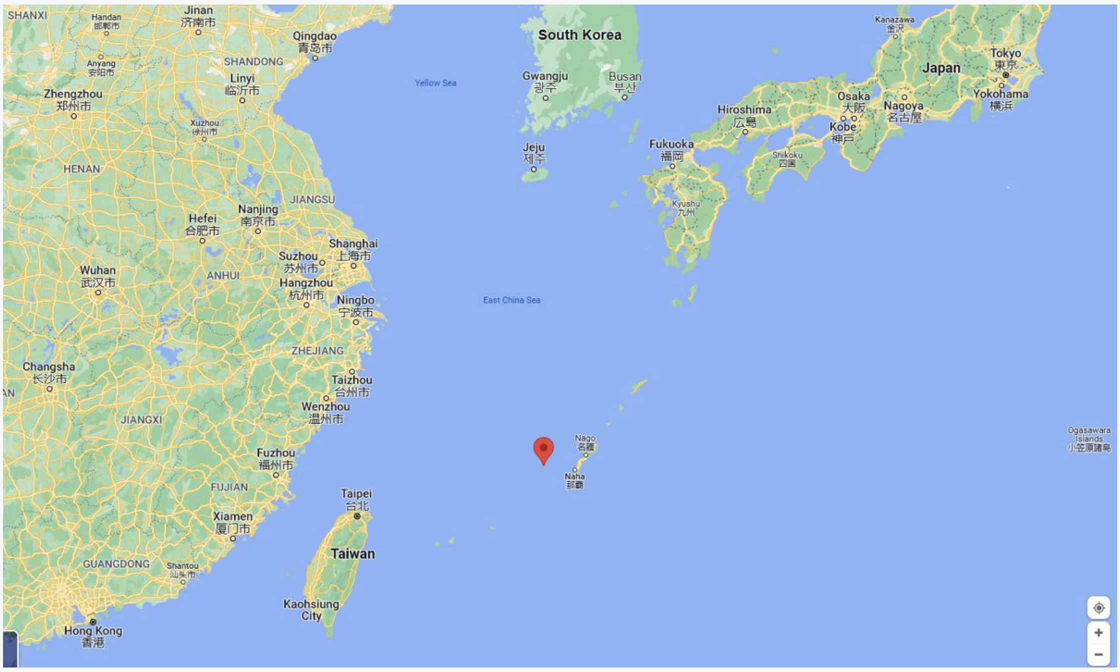


Figure 2-4: Map showing relative proximity of Kumejima Island (red marker) to Taiwan

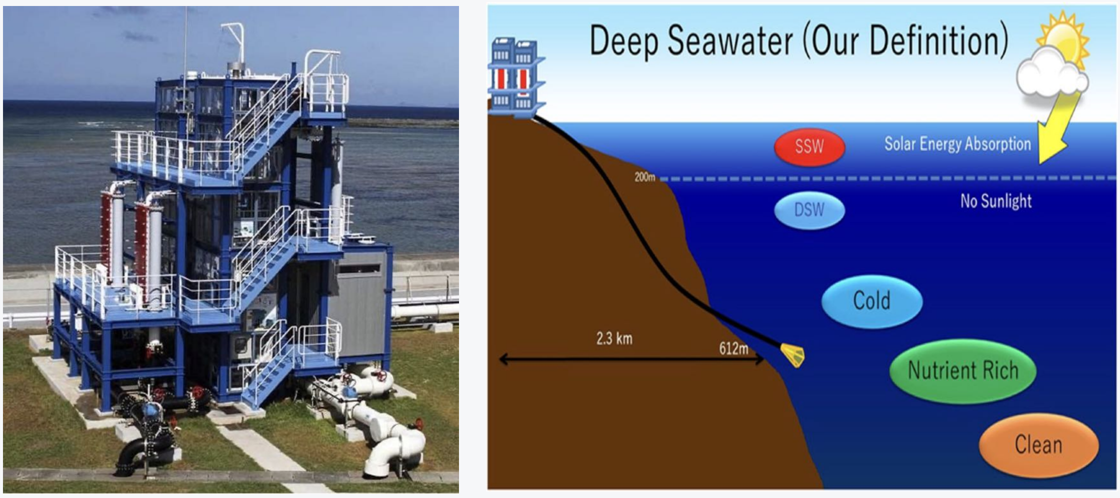


Figure 2.5: Closed cycle Okinawa OTEC demonstration facility on Kumejima Island

Figure 2.5: Closed cycle Okinawa OTEC demonstration facility on Kumejima Island

The Kumejima demonstration plant also supports several associated industries that use the warm surface and cold deep sea-water (see Figure 2-6, section 2.6).

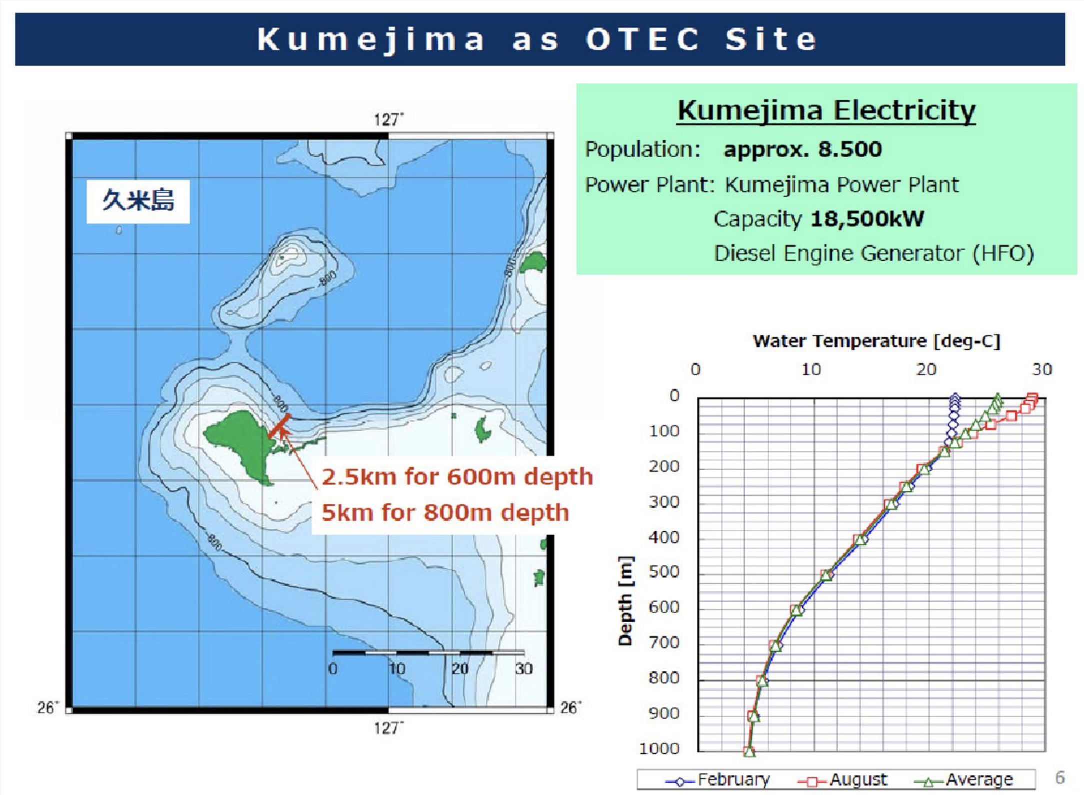


Figure 2-7 – Water depths and temperature profile at Kumejima Island. Courtesy of OTEA.

Performance of the Kumejima pipelines during typhoons

Kumejima Island, like Taiwan, experiences severe typhoons. The sea water intake pipes at Kumejima became operational in April 2013 and hence in 2022 are now over 11 years old. No significant outage/damage associated with typhoons or other events has been experienced since installation apart from normal maintenance activities to pumps, filters, and screens.

Multi-product OTEC including production of fresh water

Seawater aquaculture using nutrient-rich, pathogen-free, cold deep seawater for enhanced fish farming and algae production is a viable spin-off from the electricity production process (see Figure 2-6). Cold deep seawater discharged from OTEC condensers can also be used for district cooling, sometimes called Seawater Air Conditioning, or SWAC (see Figure 2-7). Some researchers are also working on extraction of minerals and rare earth metals from the pumped seawater, such as lithium for electric batteries. Other by-products include high value cosmetics, production of sea-grapes, abalone, etc.

In addition, by running small diameter pipes through the surface soil it is possible to irrigate via condensation from the air. This permits temperature-controlled agriculture, allowing plants to grow quickly out of season. All these by-products, particularly when their use is included at the OTEC design stage, can improve the commercial attractiveness of a multi-product OTEC plant (see ref. (7)). Both the Hawaii and Kumejima test sites are associated with significant additional product lines from the deep ocean water (see Figure 2-6 and Figure 2-8).

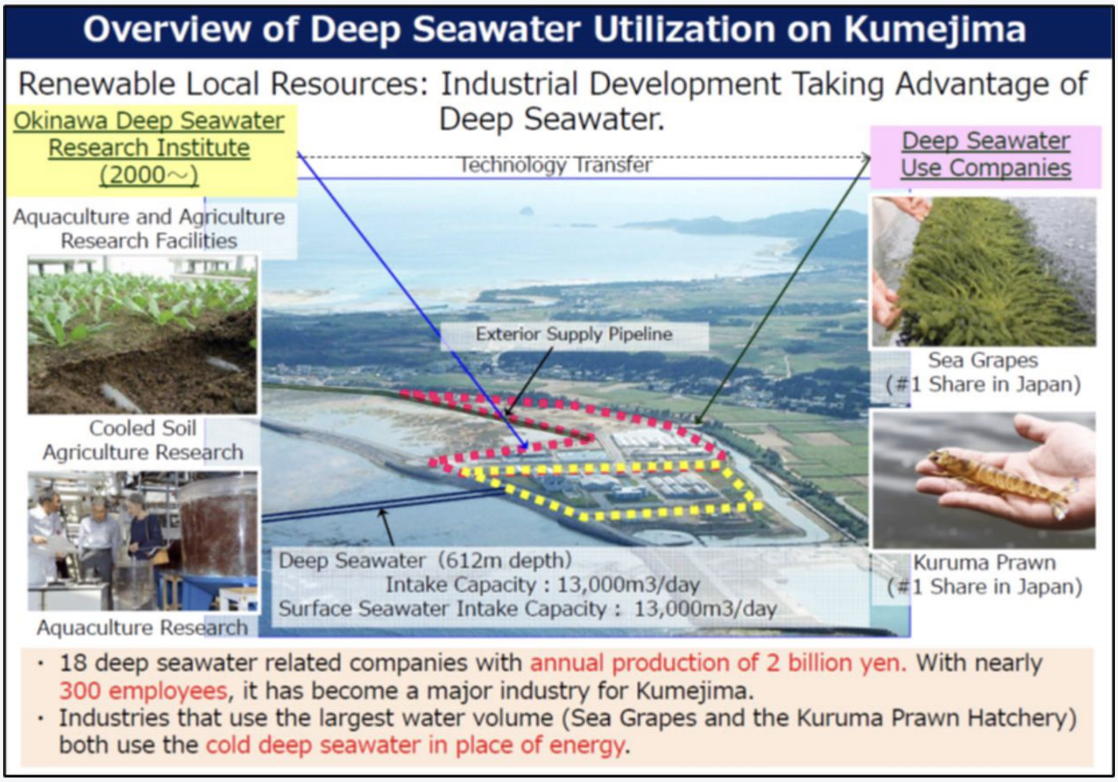


Figure 2-6 – Illustration of the multi-product nature of the Okinawa test facility. Courtesy of OTEA

Figure 2-7 shows the Taaone Hospital SWAC air conditioning system located in Tahiti in the Pacific Ocean.

This new system, which was commissioned in 2022, will save 12GWh of electricity consumption and 5,000 metric tons of CO_2 equivalent per year. .

Figure 2-7 – Taaone Hospital SWAC system on Tahiti, first operational July 2022.

Experience at the Natural Energy Laboratory of Hawaii Authority (NELHA), Kailua-Kona

NELHA has been a pioneer in OTEC research and development in the United States since 1974. It is a large 324-acre facility close to Kona Airport on the Big Island of Hawaii.

The "Ocean Energy Research Center," otherwise known as the Makai Tower, is a 100kW closed cycle OTEC facility. It was connected to the Hawaiian electricity grid in 2015 (see Figure 2-8) and utilizes the existing seawater supply systems.

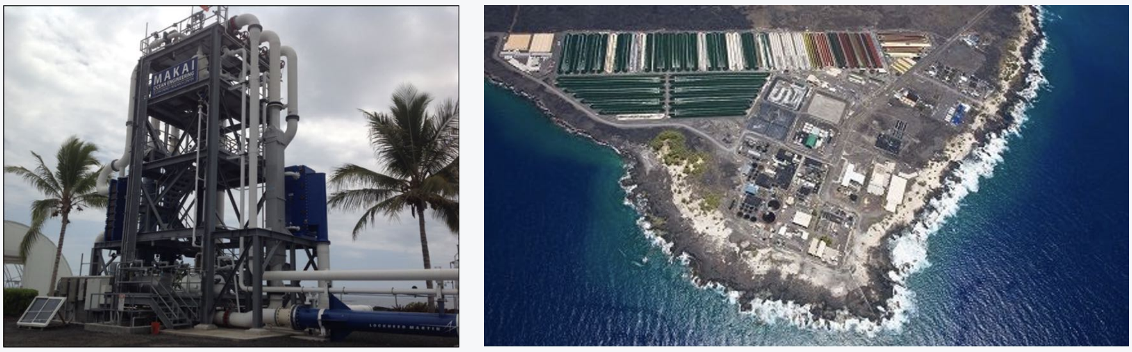


Figure 2-8 – Makai closed cycle 100kW test facility at NELHA. Right hand picture shows OTEC plus aquaculture-related facilities.

The 1m or 40-inch diameter Cold Water Pipe (CWP) that was installed at NELHA in 1988 is now 36 years old (see Figure 2-15). During this unusually long period of time the pipeline has been reliable in operation and withstood the major Kiholo Bay earthquake in 2006. The pipeline's originally evaluated design life was only 10 years. It is still in use today.

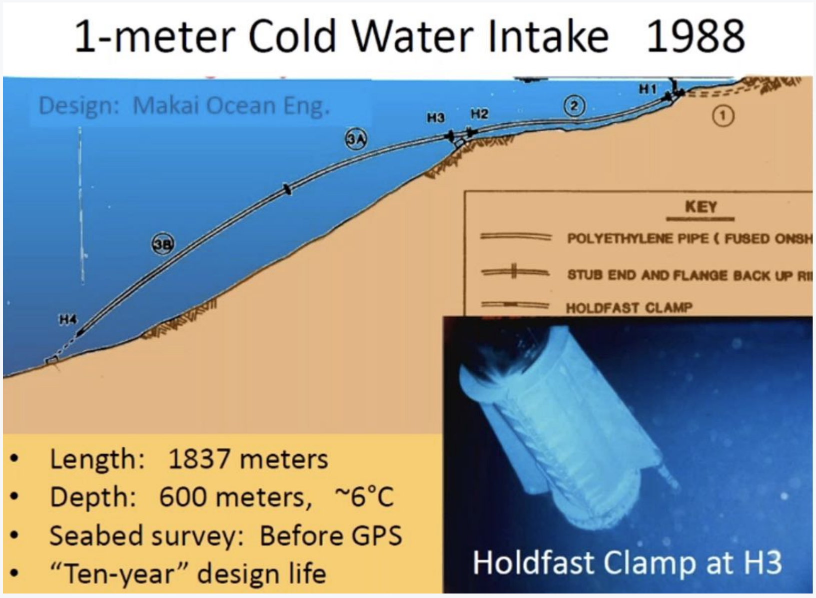


Figure 2-9: Elevation view of the 40-inch or 1m diameter CWP at NELHA.

Recent Floating OTEC Platform Tests

Figure 2-10 shows a 1MW floating OTEC barge test facility, which was successfully operated in September 2019 in South Korean waters, not far from the southern port city of Busan.

In August/September 2023 a floating OTEC test was undertaken by researchers led by the Guangzhou Marine Geological Survey on board the marine research vessel Haiyang Dizhi-2, or literally Ocean Geology No. 2 (see Figure 2-11). This test took place in the South China Sea at a water depth of 1,900m. It was reported that “the test has proved the feasibility of the country's independently developed ocean thermoelectric power generation system both theoretically and practically.”

Figure 2-11: China OTEC Test in August/September 2023 on board research vessel Haiyang Dizhi-2.

China continues to undertake OTEC R&D work at the CNOOC Research Institute Co. Ltd and at Ocean University of China (OUC) in Qingdao. It is understood that the aim of the work is to build an offshore platform powered by marine renewable energy and OTEC (see Figure 2-12).

Figure 2-12: June 2023, Guangdong Lab of Southern Marine Science & Engineering (Zhanjiang) 50kW test

Potential for 40MW Land based OTEC Power Plants

When considering the future of OTEC in Taiwan it is worth keeping in mind that larger-capacity land-based OTEC plants are possible and have been investigated in the past (see Figure 2-12).

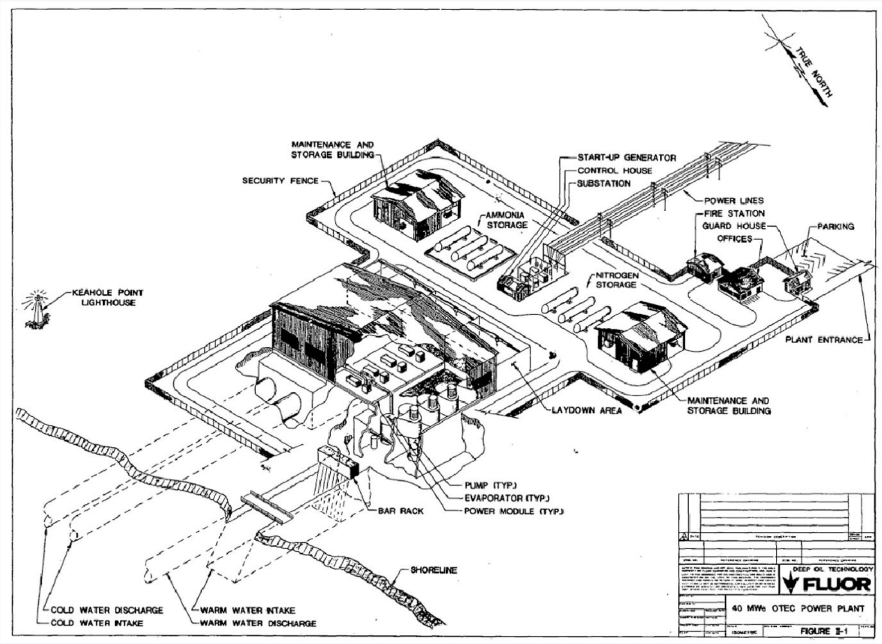


Figure 2-12: Illustration of a 40MW land-based OTEC power plant.

3 TECHNOLOGY READINESS LEVEL (TRL)

Compared to most oil and gas production the OTEC process is simple with relatively low operating pressures. Simplicity typically results in high equipment up times and high reliability, as has been seen by the OTEC plants operating in Hawaii (see Figure 2-8) and Kumejima Island (see Figure 2-4). Thus, there is a well-established track record of in field performance, although presently at a relatively small scale.

Manufacturing Large Diameter Sea-Water Intake Pipelines

Today companies such as Krah Group manufacture helical extruded (spiral wound) pipelines in diameters up to 5m. Superlit Pipe Industries manufacture Glass Reinforced Plastic (GRP) pipes in a diameter range up to 4m. These pipelines can be trenched or tunnelled through the near shore surf zone, which provides good protection. Micro-tunnelling can help to minimise near shore species disruption.

Figure 3-1: Deployment of a 3m La Taboada sea outfall pipeline in Lima, Peru. Note the size of people

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Permits and Environmental Impact Statements

The potential environmental impact of OTEC has been studied extensively over the last 40-plus years, particularly since the establishment of the Natural Energy Laboratory Hawaii in 1974. Detailed environmental impact studies have been carried out and are in the public domain. Reassuring results have also been obtained at the Okinawa Deep Seawater Research Center (ODRC) on Kumejima Island.

From a permit point of view, it is helpful that there is already a track record in Taiwan for obtaining approval for deep sea-water intakes (see Figure 2-1).

4 HOW COULD TAIWAN BENEFIT FROM OTEC

Building a Taiwanese OTEC facility in conjunction with a planned major upgrade to the Kumejima test facility

The Kumejima test facility is planned to have a major infrastructure upgrade with the work planned to be completed around 2025-2026. New seawater intake pipelines will be installed and the capacity of the plant will be increased to 1MW.

A significant cost element for any major infrastructure upgrade project is the mobilization and demobilization costs associated with the required marine and construction spread – for example, crane/lay barge, cargo barges, tugs, etc. Since the east coast of Taiwan is approximately 500 nautical miles from Kumejima there will be potential to move expensive construction equipment between the two sites, thus saving costs.

In addition, procurement for two projects permits buying in bulk with resulting purchase and transportation savings.

In addition, procurement for two projects permits buying in bulk with resulting purchase and transportation savings. In addition, it is cheaper and more efficient to use the same design team for two projects rather than just one. Therefore, it would be beneficial for Taiwan and Japan to cooperate so that an OTEC complex could be built at a suitable site on the east coast of Taiwan (or possibly on one of Taiwan's outlying islands). This project would draw on Japan's skills and experience from its work on the Kumejima test facility and would benefit from the savings on construction, procurement, and design as described above. Taiwanese input from Taiwan's major offshore wind program would also be beneficial.

Recommendations

Considerable work has been done in the past on OTEC in Taiwan. Given present-day environmental and energy security concerns, as well as the significant developments that have taken place in Kumejima and Hawaii, it is logical that the past information should be thoroughly reviewed. This will enable an up to date technical and commercial feasibility assessment to be carried out by suitable specialists for a multi-product OTEC system for Taiwan. New cost estimates will need to be generated based on present day technology, such as micro-tunnelling and high-efficiency heat exchangers.

5 CONCLUSIONS

Compared to other industrialized nations, Taiwan has ready access to deep cold ocean water on its east coast. In addition, Taiwan is relatively close to Kumejima Island, where there is an established OTEC center, which is due to receive a major upgrade to its seawater intake pipelines.

Therefore, we suggested that Taiwan approach Japan about building a new OTEC facility in Taiwan in conjunction with the upgrade work planned in Kumejima. Working together would allow for significant cost savings, which would help to improve the commercial attractiveness of the proposed new OTEC complex. In addition, Taiwanese experience from both bottom-mounted and floating offshore wind projects should be utilized.

Establishing a successful track record at a 1MW or greater scale with land based OTEC will provide the long-term operational data required to scale up to a true commercial scale. Commercial plants of 50+ MW capacity will need to be floating units; this presents a major opportunity to develop a whole new industry. Built in Taiwan Floating OTEC plants could provide major baseload electricity to the Taiwanese mainland. In addition, there is a potential significant export market for floating OTEC plant ships.

Figure 3-1: Deployment of a 3m La Taboada sea outfall pipeline in Lima, Peru. Note the size of people.

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Author - Martin G. Brown

Martin Brown is a Chartered Naval Architect, Vice Chairman of the Ocean Thermal Energy Association (OTEA) http://www.ocean-thermal.org/ and Managing Director of Ocean Energy Systems Limited, Aberdeen, UK. He has acted as a Consultant to the Oil and Gas plus Renewables Energies industry for over 25 years. Expertise includes floating production (FPSOs/FLNGs, semis and floating wind turbines), transportation and installation/removal engineering, marine warranty services as well mooring systems design and integrity.

Martin was Leader of IEC's Expert Group developing standard “Part 20: Design and analysis of an OTEC plant – General guidance” and is presently convenor to maintain and improve Part 20. In addition, he was the main author of IEA-OES's recent White Paper on OTEC, a guide for Policymakers and Developer. This paper highlights the importance of utilising deep-water oil and gas floating production expertise to reduce the technical risk and improve the economic feasibility of OTEC.

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Scenarios

In this part, we discuss the prospects, risks, and issues of various energy scenarios for Taiwan. The starting point for each scenario is the Taiwan government's Net-Zero Roadmap 2050 (hereinafter, the "Roadmap").
The overarching background in the discussion is the useful concept of Energy Trilemma, used by the World Energy Council. Under this concept, a country's energy mix can be scored within **three criteria:**

1. Energy Security reflects the nation's capacity to reliably meet current and future energy demand and ability to bounce back from shocks and supply disruptions.

2. Energy Equity reflects the country's ability to provide universal access to affordable, fairly priced, and abundant energy for domestic and commercial use.

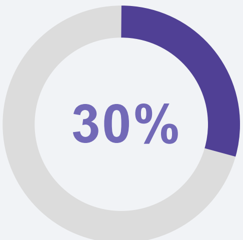
3. Environmental Sustainability reflects the ability to mitigate and avoid environmental harm and climate change impacts.

Energy sources meet these criteria in different and dynamic ways. For example, domestic natural gas production might be low cost and abundant, highly reliable and secure, and more environmentally friendly than oil or coal but worse than non-combustion-based energy sources. But if that same natural gas is shipped in as LNG from a land far away with little in the way of available storage, it might be relatively high cost and high volatility, somewhat easily disrupted either physically through blockades, terrorism, or military action, or through the global market situation. This would make it somewhat less beneficial for the climate, given inefficiencies and losses in the liquefaction, storage, and transport of the fuel.

As a simple way of adding some sensitivity analysis to the scenarios, we discuss both a Low case and a High case from the Roadmap. The Low case assumes lower targets both for energy deployment as well as for demand growth. The High case, on the other hand, assumes higher deployment and demand growth. These are taken as the low and high end of the range given in the Roadmap. The purpose is to find concrete ways to discuss the implications, identify potential gaps in demand and supply, and discuss risk management for the planned clean energy deployment, net-zero emissions goal, energy security, etc.

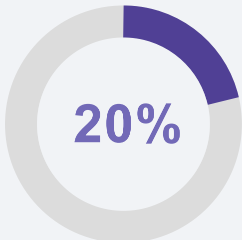
The graphs and numbers presented in the scenarios are not exact but are meant to give an overall picture of the situation with data available from public sources. For example, with clean energy deployment, a linear extrapolation is mostly used from today to the target dates of 2030 and 2050, as the Roadmap has goals set for production capacity of each key energy source for those dates. In the real world, progress is unlikely to be linear or even predictable. Some projects will proceed well while others might face delays and other problems. Policy preparation might go smoothly, or it might take longer than anticipated. Given that the Roadmap is not a purely government-driven program but relies on commercial actors for much of the deployment, this also adds to the uncertainty.

We also discuss the situation of total final energy use, not just electricity. Besides electricity, energy is used as heat (both for space heating, hot water and cooking, and as industrial-grade process steam of temperatures varying from 100°C to more than 1,000°C), as well as a mix of fuels for various types of transportation and some other uses. In the future, the use of these fuels will be more and more electrified either directly or indirectly through synthetic fuels.



Today, Taiwan uses roughly 30% of its final energy as electricity.

This is a much higher level of electrification than the global average of roughly 20% and is likely largely due to its large and electricity-hungry semiconductor industry.



We first discuss the Low case in the Roadmap as is, identifying potential issues and hopefully providing useful insights. Each clean energy source and its projected deployment is presented, gaps identified, and topics like land use, grid stability, security of supply and economics are discussed in more detail.

After that, we add one missing piece to the Low case scenario: nuclear energy. In this scenario, Taiwan also refurbishes and restarts its existing fleet of nuclear reactors, effectively canceling its current phase-out policy, which would see all nuclear reactors closed by 2025. This Nuclear Program for Taiwan is discussed in broad terms, a reasonable timeline for the refurbishment and restart campaign is identified, and its effect on the grid, emissions, and security of supply is analyzed in more detail. We aim to answer the question: How much would it help and de-risk the Roadmap if Taiwan keeps and restarts the existing nuclear fleet?

After that, the High case scenario is discussed. This assumes the highest clean energy deployment in the Roadmap, but also the highest growth in energy demand. Again, each energy source deployment is presented. While there might be hidden potential in some of the clean energy sources, it is quite clear that they have mostly been “tapped out,” especially in the High case.

Next, the Nuclear Program is applied to the High case scenario and expanded further. In addition to restarting the 6+2 existing reactors between 2025 and 2037 (the +2 are the Lungmen 1 and 2, which were never finished being built nor started, but are almost completed), a newbuild program of a further 8 GW of nuclear capacity is added, with new reactors coming online between 2038 and 2050. We again discuss how this can de-risk a lot of the assumptions in the High case.

The last scenario, Deep Decarbonization with Advanced Heat Sources explores some additional technologies that are not yet available at scale but will likely become commercially available more widely in the 2030s and 2040s. These include super-hot rock geothermal, advanced nuclear systems and small modular reactors (SMRs), floating/offshore nuclear plants, and others. This scenario focuses on replacing heat, hydrogen, and fuels still used for non-electric energy and adding flexible electricity capacity to the grid, helping to replace imported LNG and hydrogen in electricity production. We take it a bit further into the future, all the way to 2070 since the deployment of these advanced heat sources started only in 2040, growing from there.

Base Scenario – Net-Zero Roadmap 2050

The ministry's base scenario is ambitious in many ways. According to the Roadmap, Taiwan will shift from a 90%+ fossil-fueled economy (see Figure XC) to a more or less net-zero emissions economy by 2050. This relies on several assumptions regarding clean energy deployment, efficiency gains in energy use, electrification rate, economic growth and rate of industrialization, social and behavioral change, natural (and man-made) carbon sinks, and so forth.

90%+

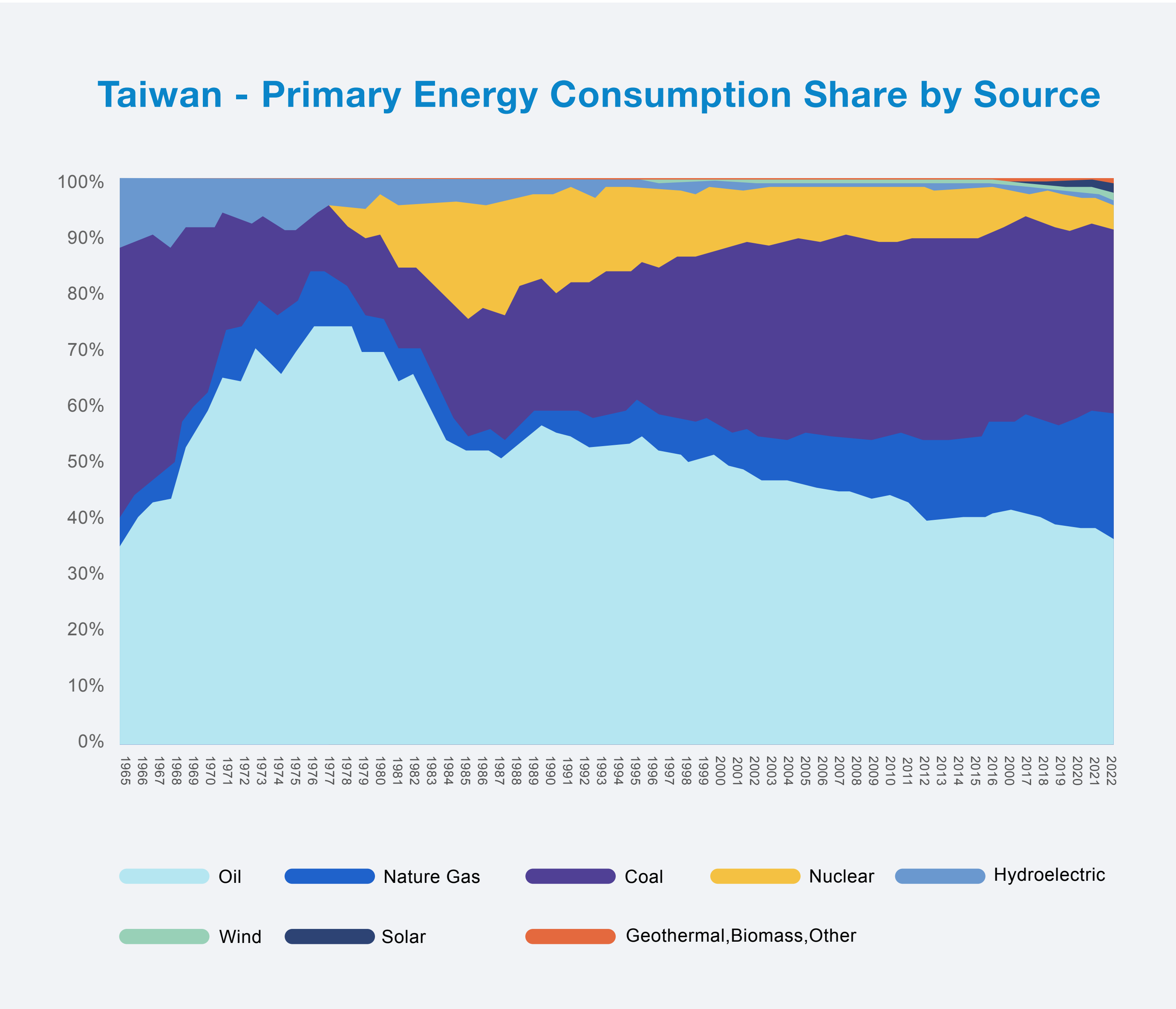


Figure 1: Historical shares of primary energy sources in Taiwan. Data: Energy Institute Review of World Energy 2023.

To put things in historical context, Figure XY presents the consumption of primary energy in Taiwan starting from the mid-1960s. As is the case with any industrializing nation that experiences robust economic growth and rising living standards of its people, energy use has grown at a significant rate. And like many industrial nations, this growth began slowing in the early 2000s.

Taiwan - Energy Consumption by Source

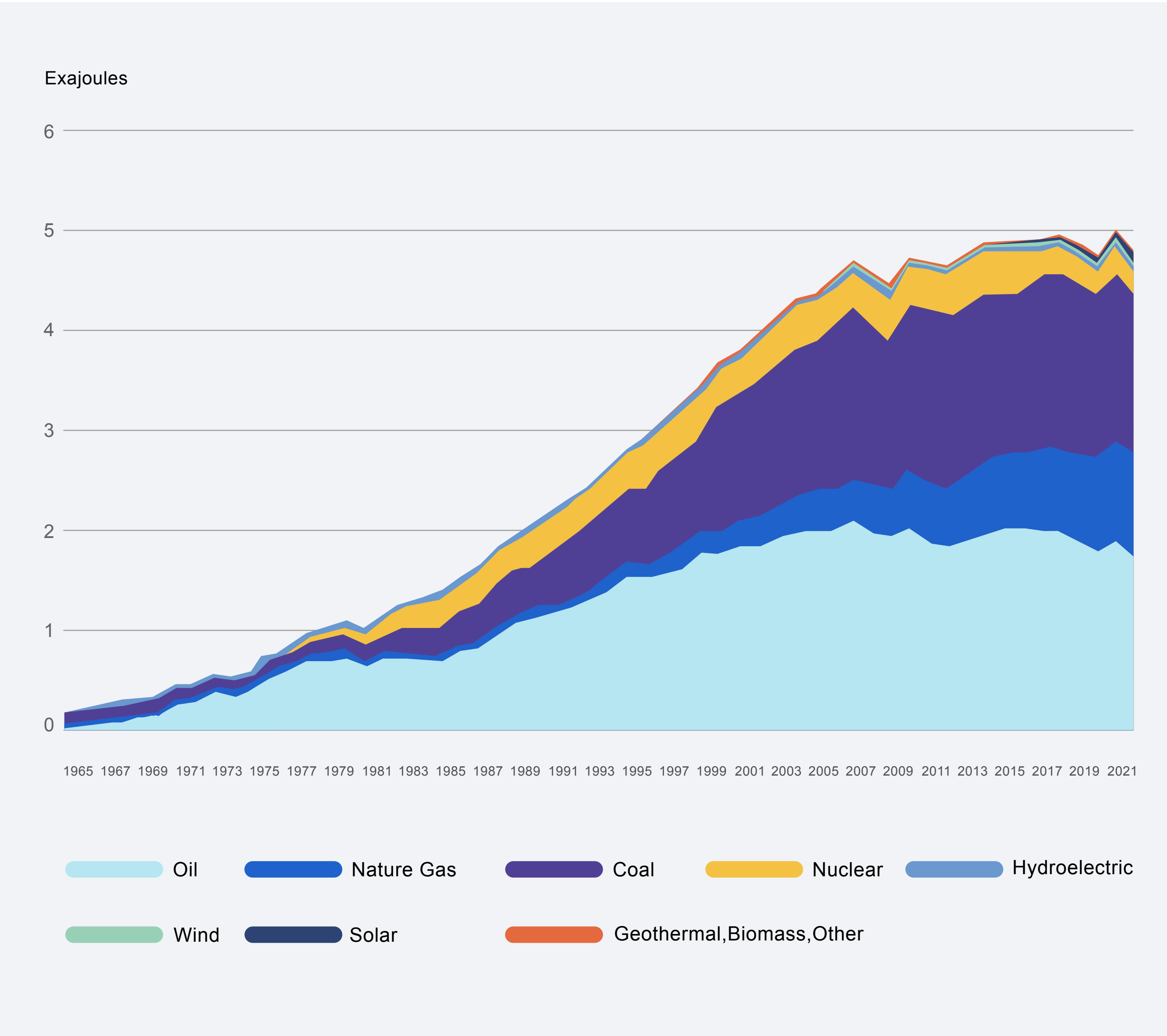


Figure 2: Taiwan's historic primary energy consumption by source. Data: Energy Institute Review of World Energy 2023.

Electricity generation in Taiwan also had an initial period of strong and steady growth until around 2007 and then one of slower growth from 2010 forward, similar to the country's total primary energy use over the same period.

Taiwan - Electricity Generation by Type

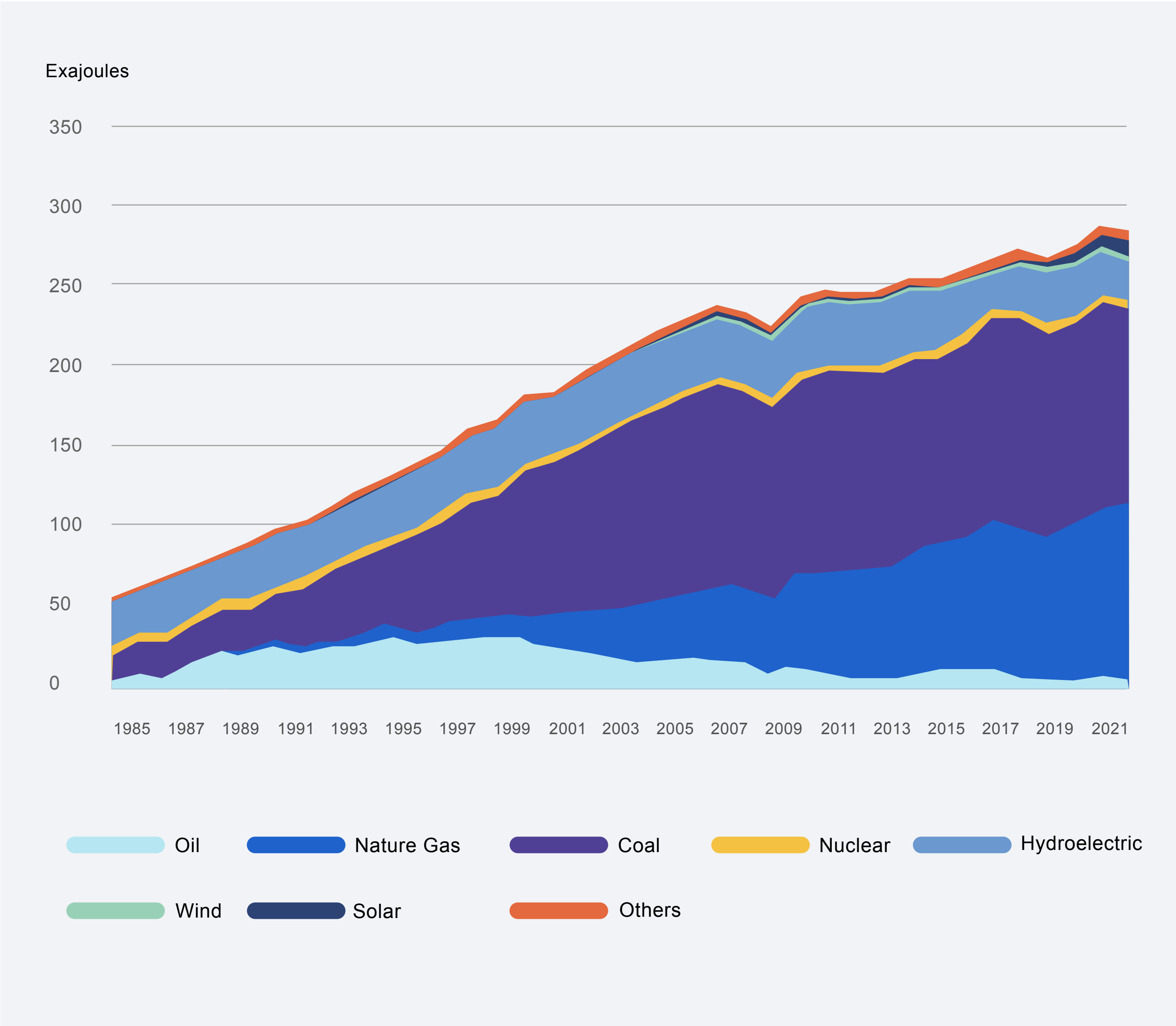


Figure 3: Taiwan's historic electricity generation by type. Data: Energy Institute Review of World Energy 2023.

The Roadmap's main tools are increasing renewable electricity production and growing carbon sinks. Clean electricity deployment will cover the growing demand for electricity as it replaces direct fossil fuel use, for example, in transportation, cooking, and industry. It will also replace current electricity generation that is based on fossil fuel combustion. Growing carbon sinks would mitigate the emissions left over from fossil fuel consumption in various sectors such as industry and transportation.

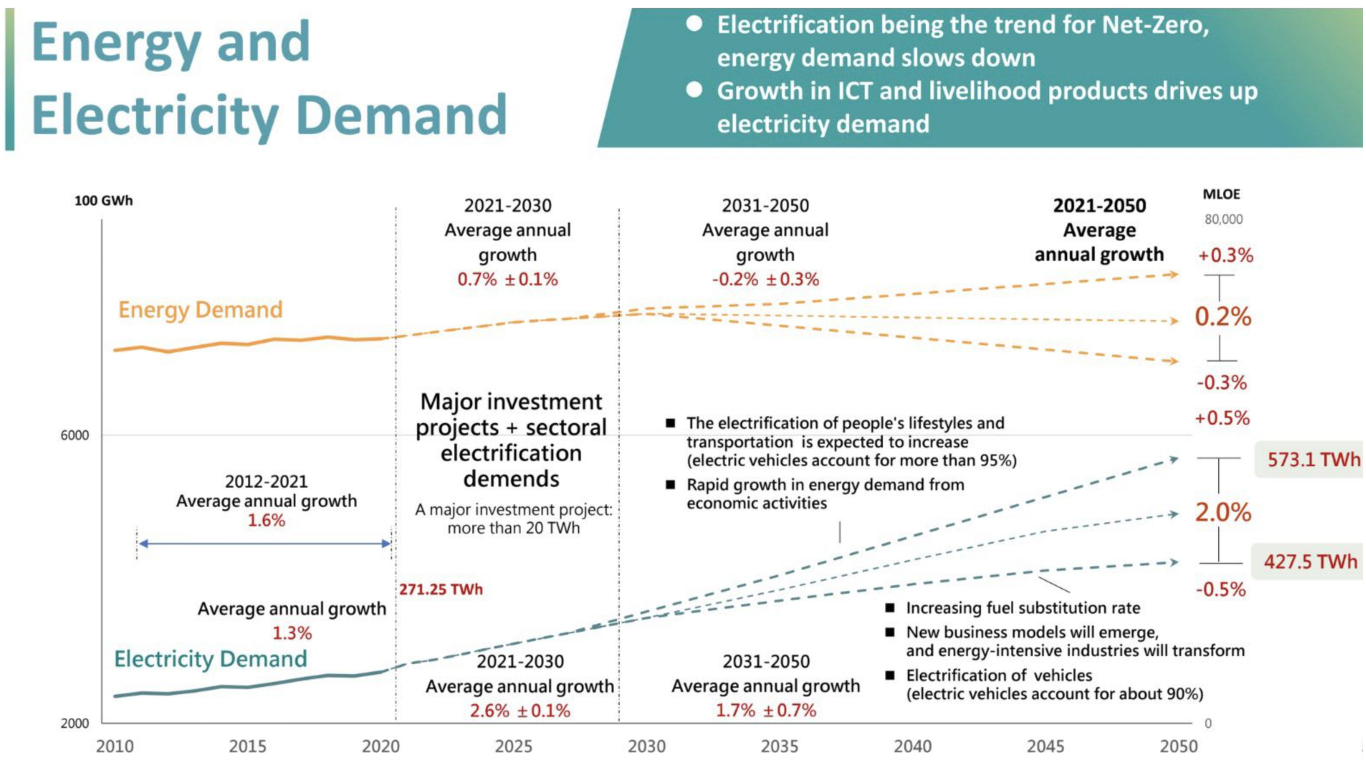


Figure 4: Energy and electricity demand projection ranges from Taiwan's Net-Zero Roadmap 2050.

Carbon Sinks

As we will later learn, a lot of fossil fuel use will remain in 2050, even in the High case scenario. To bridge the gap between the emissions from these fossil fuels and carbon neutrality, growing carbon sinks are envisaged.

The main natural sinks presented in the Roadmap are:

1. Forests. This is done mainly through increasing forest coverage, enhancing forest management, and increasing the use of timber products.

2. Soil. This is done mainly through strengthening of soil management and developing carbon-negative cultivation.

3. Ocean. This is done mainly through first developing measurement methodology of ocean and wetlands, developing fish farming business models, and by increasing ocean carbon sink management measures and promoting restoration of aquatic plants.

In addition, international cooperation is mentioned, as well as Carbon Capture and Utilization/Storage (CCUS) as part of industrial processes (not to be confused with CCUS done with electricity production, which is discussed later). International cooperation might include carbon sequestration projects, such as reforestation, undertaken in other countries and supported by Taiwan.

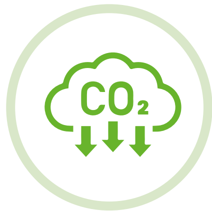
Taiwan's carbon sinks are mainly in its forests and were estimated to be roughly 22 million metric tons in 2020, according to the Roadmap. This is largely a result of the reforestation campaign Taiwan has had in the past, as the trees planted then are now growing fast.

22 Million

The problem is that at some point, tree growth slows down, and the annual sinks start to get smaller. In other words, the forest's "carbon storage" capacity fills up. This happens unless trees are cut down periodically, and new ones planted. This type of forest management, if done well, will keep the annual sink of the forests stable, provide timber and other wood products for industrial/construction use, and never fill up the carbon storage in the forest.

Open questions remain, however, such as what happens to the amount of carbon in the forest soil over time and how forest management practices affect the carbon stored in the soil. The overall carbon sink in the long term is also affected by the amount of harvested wood that ends up in long-lifetime products like buildings and furniture. In the case of bioenergy, paper, and cardboard, the carbon sequestered by the plants is returned to the atmosphere within a couple of years after they are harvested.

The overall net carbon sinks in the Roadmap are projected to grow almost three-fold by 2050, to 62.7 million metric tons of CO2 (see Figure XZ). This relies on other sinks besides just forest growth, such as soil carbon, the ocean, industrial carbon capture and use/storage, and international cooperation projects.



62.7 Million

Projected Annual Net Sinks from Forest , Soil , Ocean , CCUS , and International Co-op

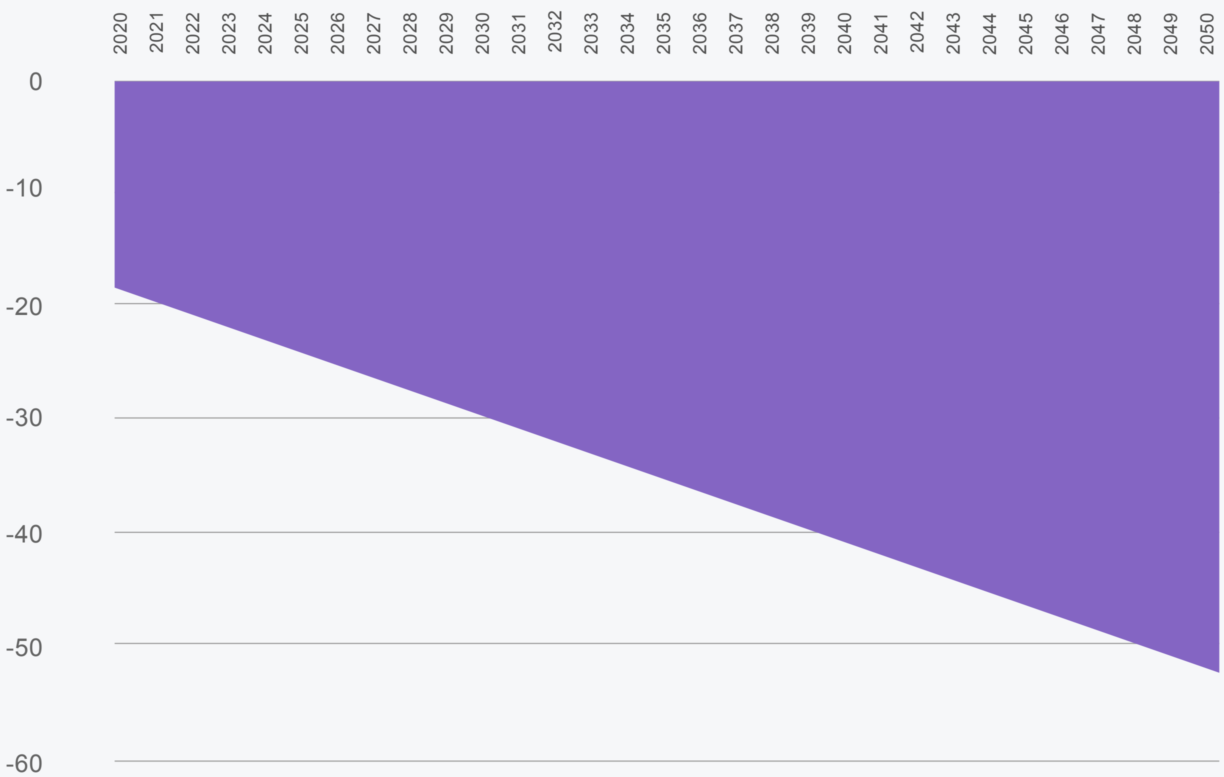


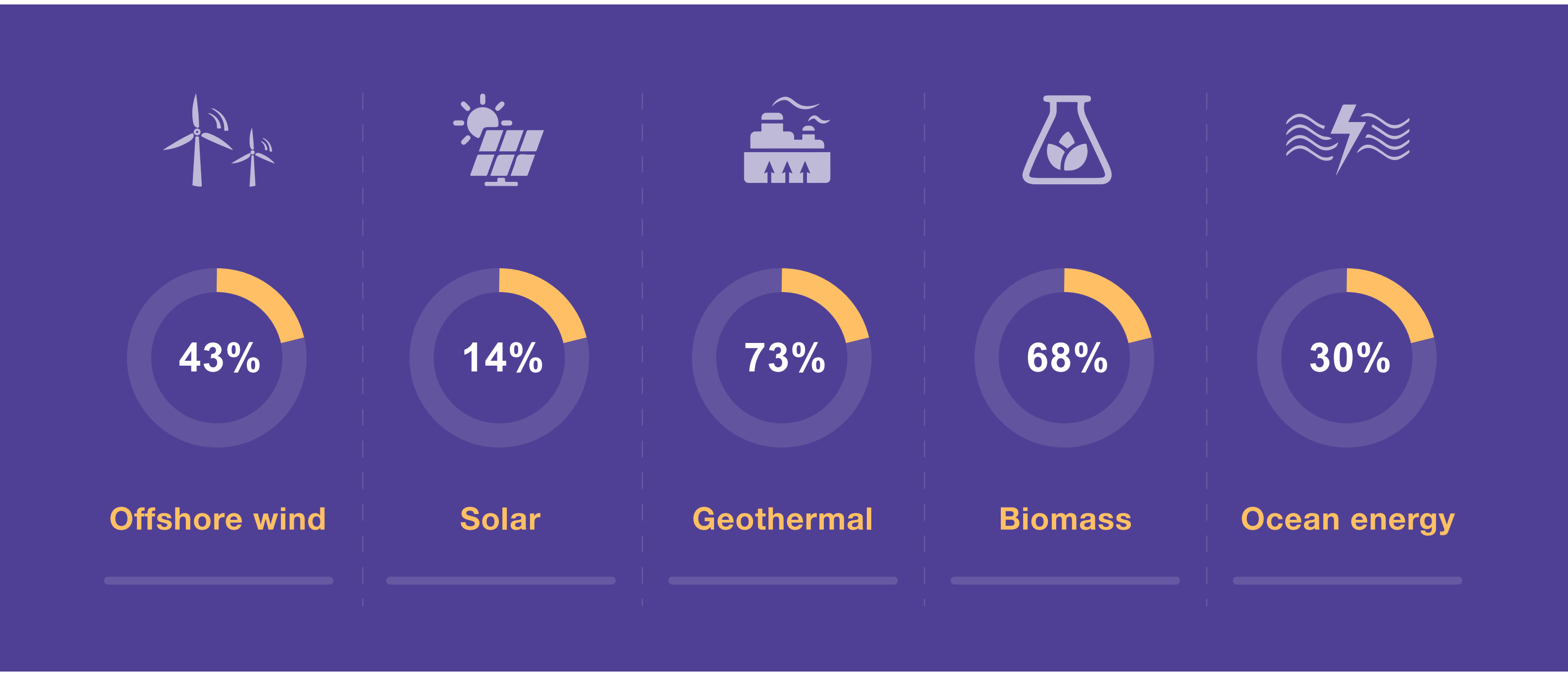
Figure 5: Projected net carbon sinks in Taiwan, growing from 22 million metric tons of CO2 in 2020 to 62.7 million metric tons by 2050.

These other carbon capture methods are often even more uncertain than forest growth. For example, there are significant uncertainties about how much more carbon can be stored in agricultural soils through carbon-negative farming, how cost-effective it will be, and how well the soils will retain the carbon over the long term.

Industrial carbon capture and utilization/storage might offer some substantial increases, but it has its downside as well. Capturing carbon uses significant amounts of energy and is quite expensive, at least for now. Storing that carbon requires suitable storage and geology while transporting very large amounts of CO2 for long distances increases costs further. If the carbon is utilized for chemicals or synthetic fuels, it is often not stored for long as it quickly gets released back into the atmosphere.

Capacity and Energy Production

The CFs used are below:



The Roadmap has targets for adding clean energy production capacity by certain dates (2030, 2050). It also gives estimates of how much emissions will be avoided by adding the targeted amount of capacity, assuming it replaces grid electricity with emissions of 502 grams of CO2 per one kilowatt hour of electricity (gCO2/kWh). We used these numbers to calculate the assumed average capacity factor (CF) to find out how much each megawatt of wind, solar, etc. will produce each year. For example, if a power plant runs at full power half of the time, its CF is 50% (or 0.5).

It can be argued that the CFs for offshore wind and perhaps solar are on the conservative (low) side, as excellent offshore wind locations with very large turbines can reach CFs of 50%, or even higher. With a very large wind turbine fleet, it might be prudent to assume a lower average CF over long periods of time due to maintenance and some turbines being in a bit less optimal locations, turbines potentially disrupting each other's production, and other factors.

50%

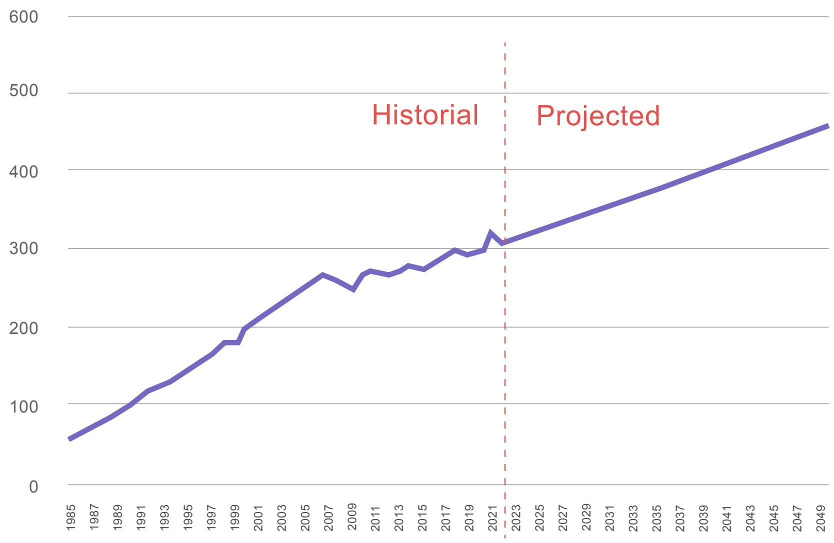
The same goes for solar: a large fleet of solar panels is unlikely to be sited wholly in optimal locations, with optimal tilt and direction (or perhaps even the panels that track the sun). In particular, rooftops and other urban environments are often not optimal for solar panels from an energy production maximizing perspective. In addition, production greatly depends on the technology used in the panels. And the number of sunny days in Taiwan also varies quite significantly depending on the region.

To mitigate production variability, the Roadmap also includes targets for energy storage, but only for 2025 (1,500 MW) and 2030 (5,500 MW) in total, including batteries and generators. Given how critical these technologies will be with such large shares of wind and solar, the roadmap could have more substance and details.

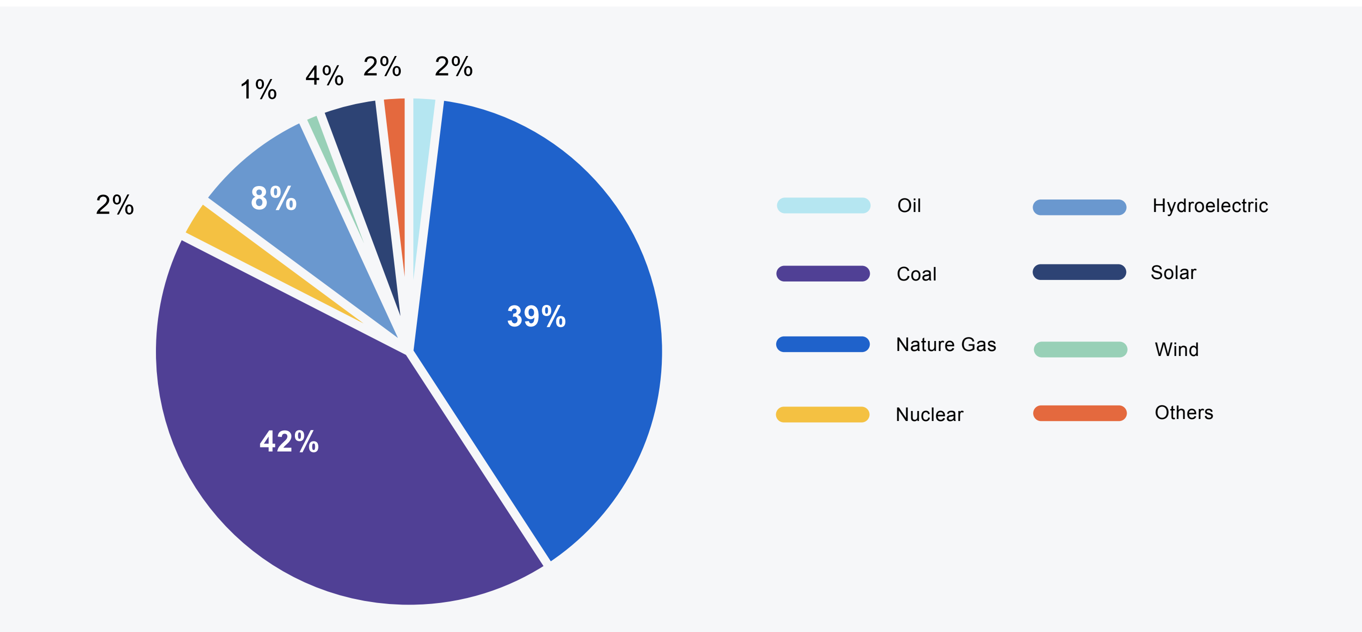
Low Case

The Low case has electricity demand growing from around 280 TWh/year today to 428 by 2050. This is a compounded annual growth rate of roughly 1.4%. It is similar to what Taiwan has experienced during the last 15 years, but slower than the rate before that (see Figure ZX).

Taiwan's Historic and Projected Electricity Generation Net - Zero 2050 Roadmap , Low case



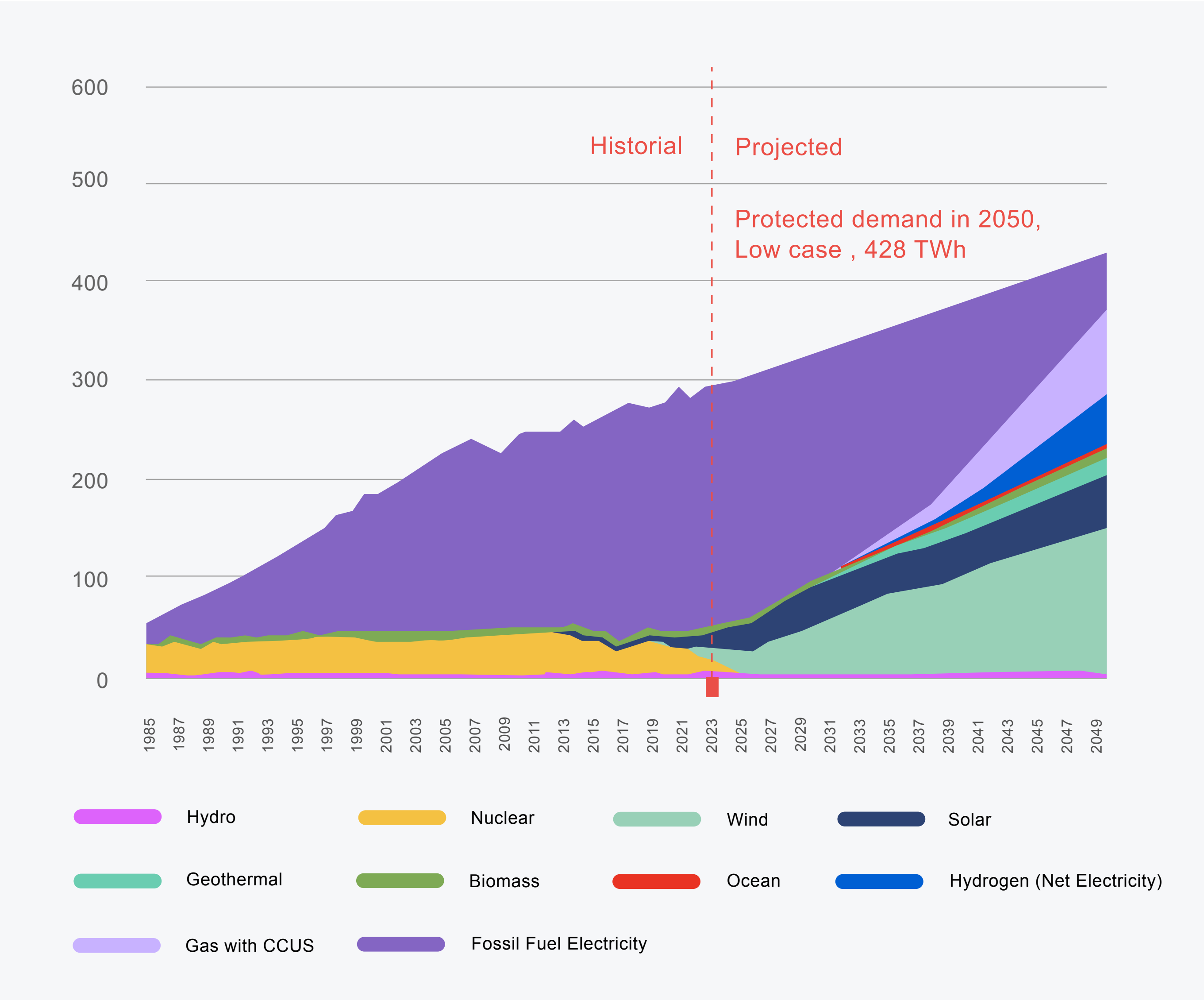
Taiwan - Electricity Generation Share by Type 2022



As can be seen in Figure ZX, Taiwan's electricity production is currently ~83% based on fossil fuels. This is a much higher share of fossil fuels than the global average of 60%. To add to that, practically all of the fossil fuels are imported, making Taiwan extremely import-dependent for its electricity.

Figure ZXC below shows how each energy source would grow between 2023 and 2050. The growth rate is extrapolated from each energy source's Net-Zero Roadmap 2050 targets. To keep it simple, additions are assumed to happen in a linear fashion. Additionally, the shrinking amount of fossil fuel electricity generation is also shown.

Taiwan's Historic and Projected Electrcity Genration by Sourse Net - Zero 2050 Roadmap , Low case



In 2022, Taiwanese clean electricity production was roughly at the historical level it has been at for almost four decades. Nuclear capacity has been closed recently, but solar and wind capacity has been added. Below, each of the clean energy sources and their deployment are discussed in more detail.

Offshore Wind

In 2022, Taiwanese wind capacity stood at 1,581 MW. In the low case, offshore wind capacity will increase by 1,440 MW per year between 2022 and 2030, resulting in 13,100 MW in 2030. From 2030 to 2050, the average annual increase is 1,345 MW per year, resulting in a total capacity of 40,000 MW. These are significant numbers given that in 2022 the total installed wind capacity of Taiwan, at 1,581 MW, was just slightly more than the projected average annual additions for the next 27 years. The total electricity production from this capacity depends on the average CF of the wind turbines, which in turn depends on turbine size, placement, wind conditions, and other variables. We estimate roughly 150 TWh of production per year for the 40 GW of capacity.

Assuming a large offshore wind turbine's average operational lifetime is 30 years, after 2050, a similar rate of annual installments would be needed to keep the fleet the same size, replacing retiring turbines.

Land use, or in the case of offshore wind, use of sea area, can become a major issue. Only the seabed west, northwest, and north of Taiwan – basically the Taiwan Strait – is well-suited for large-scale offshore wind installations, as sea levels there are relatively shallow. Indeed, some analysts have said that there is only space for roughly 12 GW of offshore wind around Taiwan that can be installed to the seabed. The rest would have to be floating offshore wind, which is much more expensive than seabed-installed wind. The National Renewable Energy Labs (NREL) Cost of Wind Energy Review 2021 -report cites Levelized Cost of Electricity (LCOE) of $78 for fixed-bottom offshore wind and $133 for floating offshore wind .

Figure XZ shows the rough area that offshore wind and solar parks would take in 2030 and 2050, overlaid on Google maps.

The areas needed are:

2030 Wind at 13,100 MW

6,092 km2

2050 Wind at 40,000 MW

18,600 km2

2030 Solar at 31,000 MW

930 km2

2050 Solar at 40,000 MW

1,200 km2

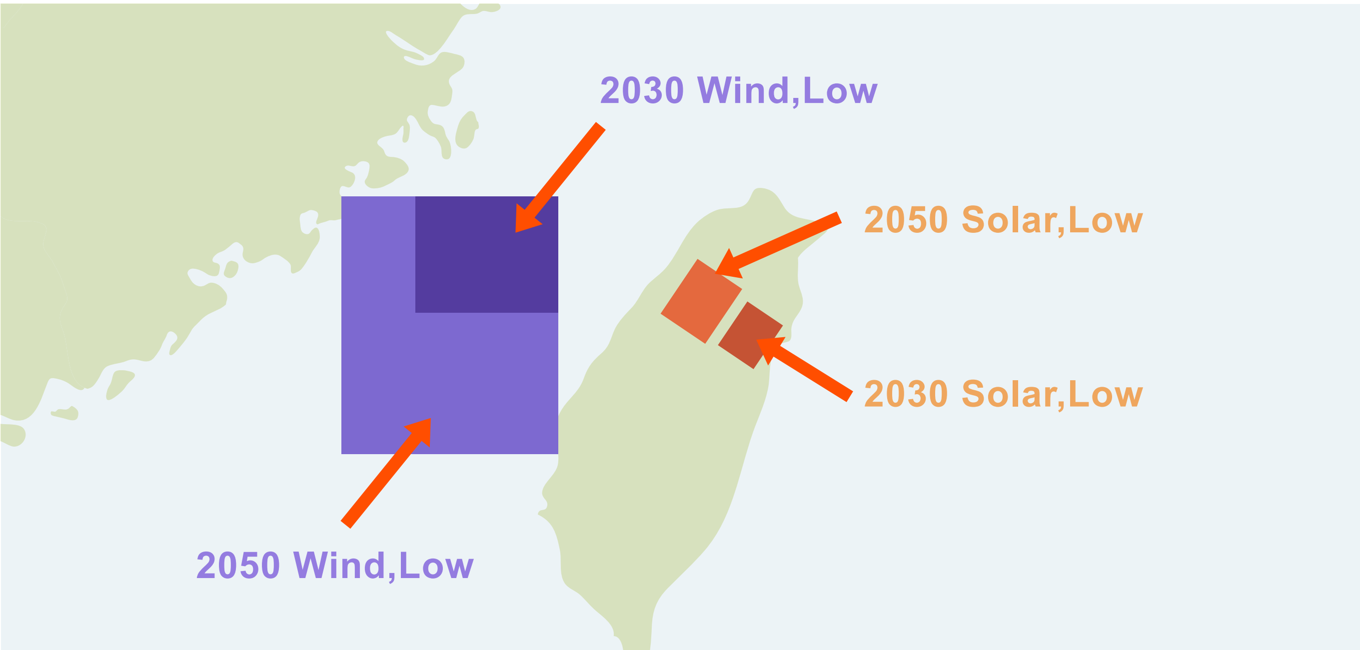


Figure 7: The area required by offshore wind and solar PV in the Low case scenario, for years 2030 and 2050.
In reality, the parks would not be a single entity, and would therefore take even more overall space.

The offshore wind area is calculated using the UK's Dogger Bank wind farms (A, B, and C) as a proxy. Dogger Bank is the world's largest offshore wind project, and the UK has very good offshore wind resources, so using it as a proxy might lean more toward the optimistic. These three offshore wind farms in the UK will have a total capacity of 3,600 MW and take an area of 1,674 km2. On average, the power density will be 2.2 MW per km2, and the parks are estimated to produce roughly 9 GWh/km2/year, although Dogger Bank has a higher assumed CF. Solar area is calculated by assuming three hectares per megawatt, including access roads and such in addition to the panels.

Solar

In 2022, Taiwanese solar capacity was at a respectable 9,724 MW. The low case for solar power is an annual increase of 2,660 MW between 2022 and 2030, for a total capacity of 31,000 MW. After that, the annual increase would slow down to 450 MW per year, leading to a total capacity of 40,000 MW in 2050.

Solar panels lose their efficiency over time and so will also need to be replaced at some point. To replace a 40,000 MW fleet with an operational lifetime of 30 years, around 1,330 MW of repowering or new solar installations will be needed annually from roughly 2045 onwards.

Land use could become another critical issue for solar expansion over time. This is mainly an issue in densely populated areas, which constitute much of Taiwan. While solar has a much higher energy density than wind parks (which need a lot of space between turbines to work well), they still require significant amounts of surface area – much more than can be afforded by rooftops and walls in urban, populated areas. Besides urban areas, Taiwan has agricultural land for food production and forests that produce timber and/or carbon sinks and increase biodiversity, depending on how they are managed.

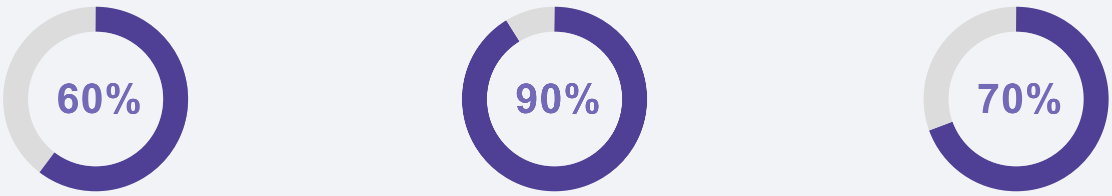
With land use, the question is not about choosing between one kind of use and another – for example, between agricultural land and solar parks. Rather, it is about finding the best overall use for a given area of land, considered in combination with the surrounding areas and how they are used now and in the future, and with regard to the overall goals of the nation, region, and local community. There are also considerations like conservation and aesthetic values, given Taiwan’s natural beauty. The amount of land used for solar installations in the Low case scenario in 2030 and 2050 can be seen in Figure YZ above.

Other Domestic (Biomass, Geothermal, Ocean)

The Low case scenario also assumes production from several minor energy sources, namely biomass, geothermal, and ocean energy. Biomass is already a minor source of energy in Taiwan. It is estimated to grow from ~4.9 TWh in 2022 to 8.4 TWh in 2050, at least partly through imported fuel. Ocean energy starts to emerge around 2030, growing rather slowly to around 3.4 TWh/year in 2050. It should be noted that so far, Ocean energy is unproven at scale. Geothermal is the most significant source, starting off relatively slowly today and growing to 19.3 TWh by 2050.

Imported: Hydrogen

The scenario assumes around 51 TWh of electricity generation from imported hydrogen by 2050, 12% of the total electricity generated.



Fuel Cells | **Liquefaction, Transport, and Storage** | **Electrolyzers**

Assuming 60% efficiency for the fuel cells to turn hydrogen into electricity, 90% efficiency in liquefaction, transport, and storage, and 70% efficiency for the electrolyzers to make the hydrogen from electricity, roughly 135 TWh of clean electricity is needed to make that amount of hydrogen. It also assumes that starting in 2039, the share of hydrogen will grow by 1% of total electricity generation each year.

A big problem with hydrogen is that it first needs to be manufactured somewhere. While clean hydrogen production is on the rise, some 95% of global hydrogen is still produced from fossil fuels with significant CO2 emissions. It might take decades to replace current hydrogen use with clean alternatives before it makes sense to start making clean hydrogen at scale for new uses, such as transporting it into Taiwan.

Long-distance transport is another issue, as hydrogen is hard to transport due to it being a very small and volatile molecule capable of leaking through and embrittling most materials over time. It would also need to be stored in large quantities in Taiwan to be used at times when wind and solar production is low and/or demand is high. Importing and storing hydrogen will be more complicated and riskier than natural gas, although using it does not create emissions.

A significant part of the hydrogen might be imported and stored as ammonia. In addition to making fertilizers and other chemical uses, ammonia can also be used as a fuel to produce electricity, for example through co-firing it in coal plants, although it is not yet common . Ammonia is easier to transport and store than hydrogen. Hydrogen can also be relatively easily separated from ammonia for direct use.

Imported:
Natural Gas with Carbon Capture and Utilization or Storage

Starting in 2031, the Low case scenario sees steadily increasing electricity generation from natural gas with carbon capture and utilization or storage (CCUS). It starts at 1% of total electricity generation in 2031 and increases by 1 percentage point each year after that, reaching a 20% share in 2050, or 85.5 TWh. As is the case with natural gas in Taiwan today, it is imported as LNG.

There are several potential problems with natural gas and carbon capture. First, the process is not 100% efficient. According to the United Nations Economic Committee for Europe's (UNECE) recent study, electricity produced with a combined cycle natural gas turbine equipped with carbon capture and storage (CCS) has lifecycle emissions of 128 gCO2/kWh, which is ten times higher than sources like wind and nuclear. The carbon capture uses energy, adding to costs and decreasing the amount of net electricity one gets from combusting natural gas.

Given the very large share of wind and solar even the Low case scenario involves, it is likely that a significant share of natural gas electricity generation would be used fill in the gaps left by wind and solar. This type of flexible load-following can't be done with the more efficient combined cycle gas turbines but would be done with the simpler open cycle turbines. There is also the question of how feasible it will be to efficiently perform carbon capture if the production is constantly ramped up and down. The 128gCO2/kWh taken from the UNECE report might be on the lower end, as it is a number given for combined cycle use, which is usually a stable baseload, and does not include any emissions from the LNG transportation.

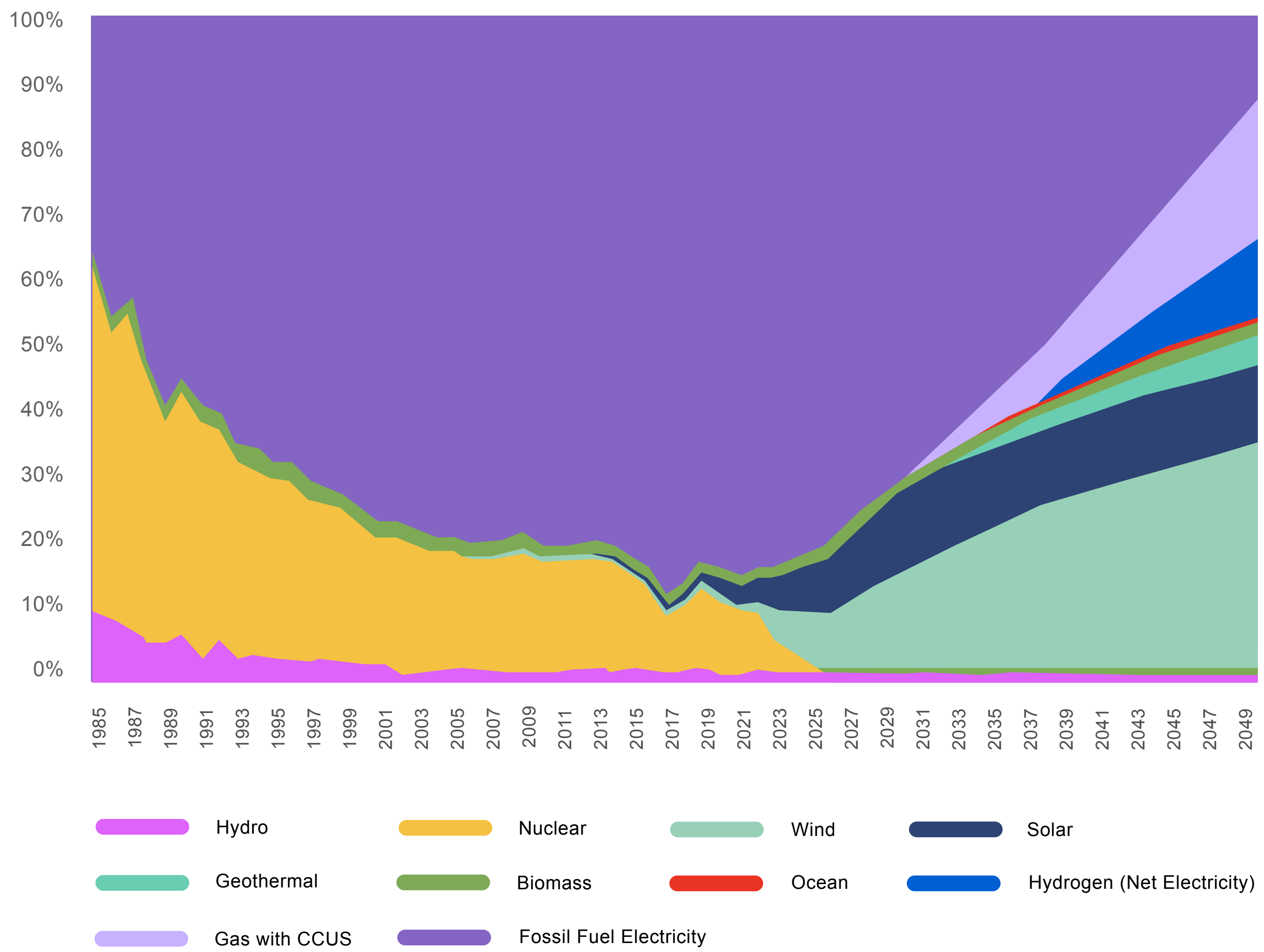
Finally, the captured carbon must somehow be stored or used. This is not a new idea, as CO2 has been injected into older oil wells for decades to enhance their production (called enhanced oil recovery, EOR). The main question is whether suitable geologies and formations exist nearby, whether the CO2 needs to be transported over long distances for storing, and what the cost will be for the transportation and the storage service.

Fossil Fuel Generation

The Low Case sees a remaining 55 TWh/year share of fossil fuel electricity generation in 2050. This will be mostly imported fuels. When combined with imported natural gas with CCUS and hydrogen, roughly 190 TWh of electricity will be generated with imported fuels, or around 44% of total generation. This is a big improvement from the situation today (~95% imported). Then again, the imports will mostly be LNG and hydrogen, which are much harder to store than uranium fuel or even coal. As this is combined with the heavy reliance on weather-dependent renewables, this decreases the energy system's security of supply and reliability.

Figure CV shows the shares of different electricity sources, both historical and future projections for the Low case scenario.

Taiwan - Shared of Energy Sources in Electricity Generation Net - Zero Roadmap - Low Case



Final Energy Use

In the Low case scenario, total final energy consumption is projected to be slightly lower than today, first increasing in the 2020s (0.6 % per year) and then decreasing after 2030 at -0.5% per year (see Figure QW).

Taiwan - Shared of Energy Sources in Electricity Generation Net - Zero Roadmap - Low Case

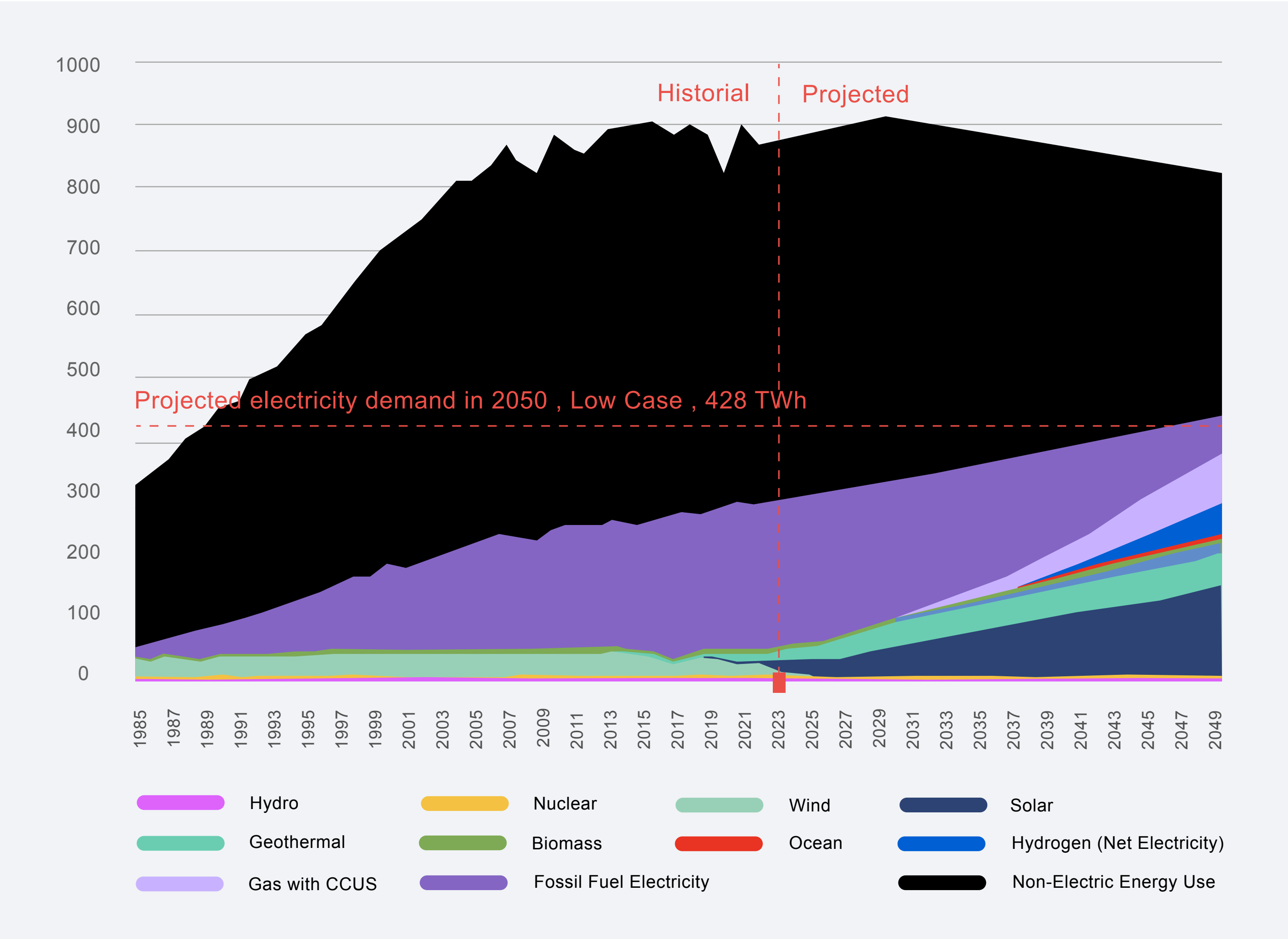


Figure 9: Taiwan's historical and projected end use energy, with electricity generation separated by source and the rest included as a single category. Data: Energy Institute Review of World Energy 2023 and Net Zero 2050 Roadmap. Final energy use is adapted from primary energy use data, according for thermal losses in thermal power plants.

As can be seen in Figure QW, there is a significant amount, roughly 48% or 399 TWh, of non-electric energy use left in 2050. This is mostly consumed as various fossil fuels, and mostly in what are called “hard-to-electrify” sectors. These include fuels in non-EV transportation, cooking and heating in regions with natural gas pipelines and boilers, fuel use in the petrochemical industry and refining, glass making, cement, iron and steel, heavy machinery, marine shipping, and long-distance aviation, to name some of the bigger ones.

Figure ZX shows the annual average changes in Taiwan's energy mix between 2022 and 2050.

Some of the more significant changes include:

+5.2 TWh / year
Offshore wind

+3.1 TWh / year
Natural gas with CCUS

+1.8 TWh / year
Hydrogen for electricity production

+1.4 TWh / year
Solar

+0.7 TWh / year
Geothermal

-0.9 TWh / year
Nuclear

Overall fossil fuel electricity generation and non-electric fossil fuel use both decrease by around 6.5 TWh/year. Clean electricity increases at 11.6 TWh/year, while net electricity generation increases by 5 TWh/year.

Auunal Average Change in Energy Use by Source 2022 - 2050 - Low Case

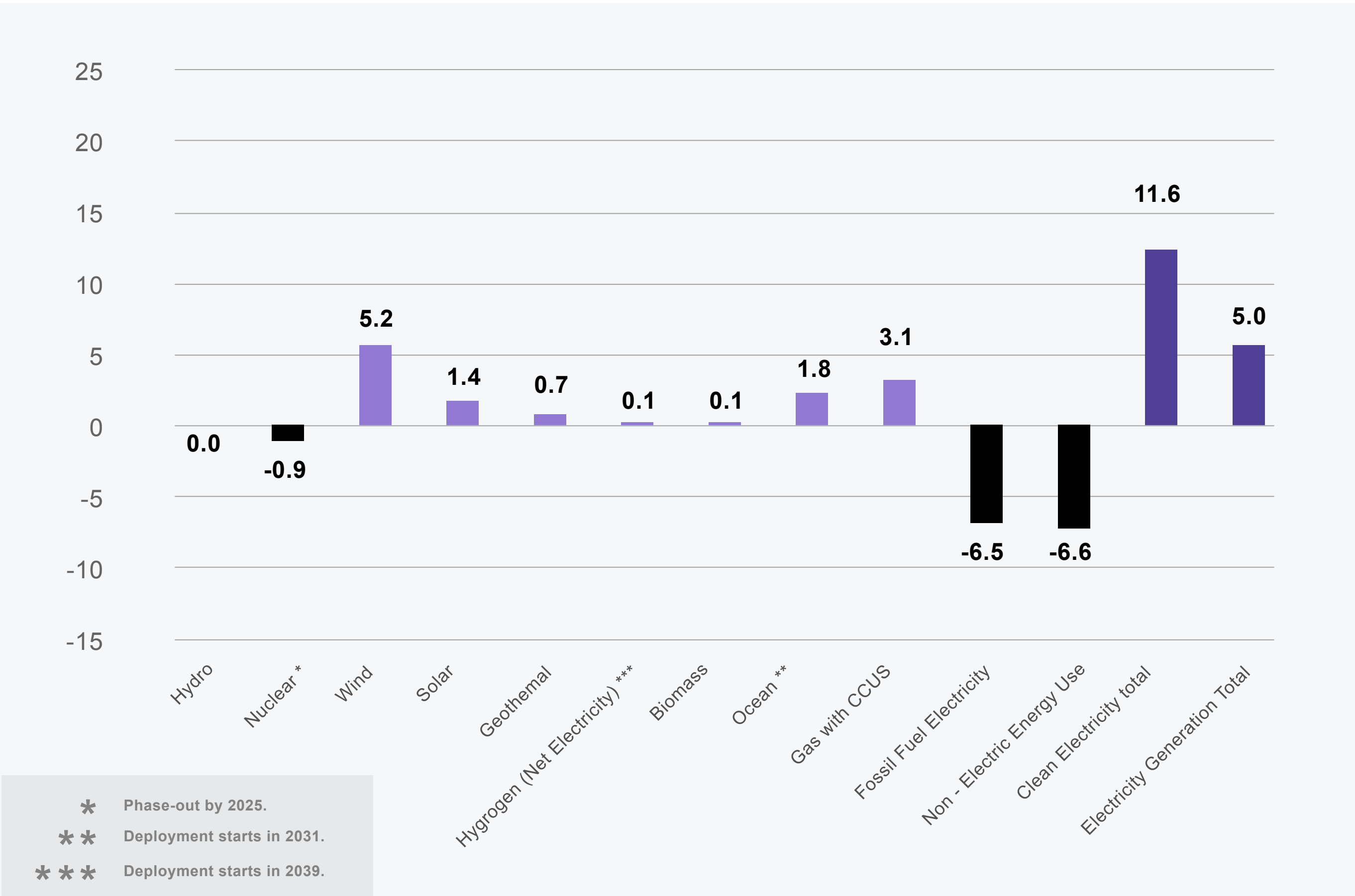


Figure 5: Projected net carbon sinks in Taiwan, growing from 22 million metric tons of CO2 in 2020 to 62.7 million metric tons by 2050.

Final Energy Use

The term Final Energy Use refers to the final energy product that is used by the customer. The form, or carrier, of that energy is usually either electricity, liquid fuel (for transportation or heating), gaseous fuel (for example, cooking on a gas stove or space heating), or heat (either in the form of heated water for space heating or steam for other purposes, such as industrial processes).

Discussion on Low Case Scenario

The Net-Zero Roadmap 2050 Low case scenario offers an illustrative view into the larger decarbonization problem. While the scenario and deployment rates of various technologies and carbon sinks seem quite ambitious, it is also clear that it is not fast enough if the goal is actually net-zero emissions by 2050. The Roadmap relies too much on everything going more or less optimally.

For example, offshore wind is assumed to grow at very high rates. This is assumed to happen mostly through outside investments. For a while these investments were being made, thanks to Taiwan's then very generous feed-in-tariffs (FiTs). But those tariffs have been removed while demands for a significant localization of the supply chain remain. This in turn increases development costs significantly. Suddenly, Taiwan has shifted from being one of the more desirable places to invest in offshore wind to one of the more expensive ones.

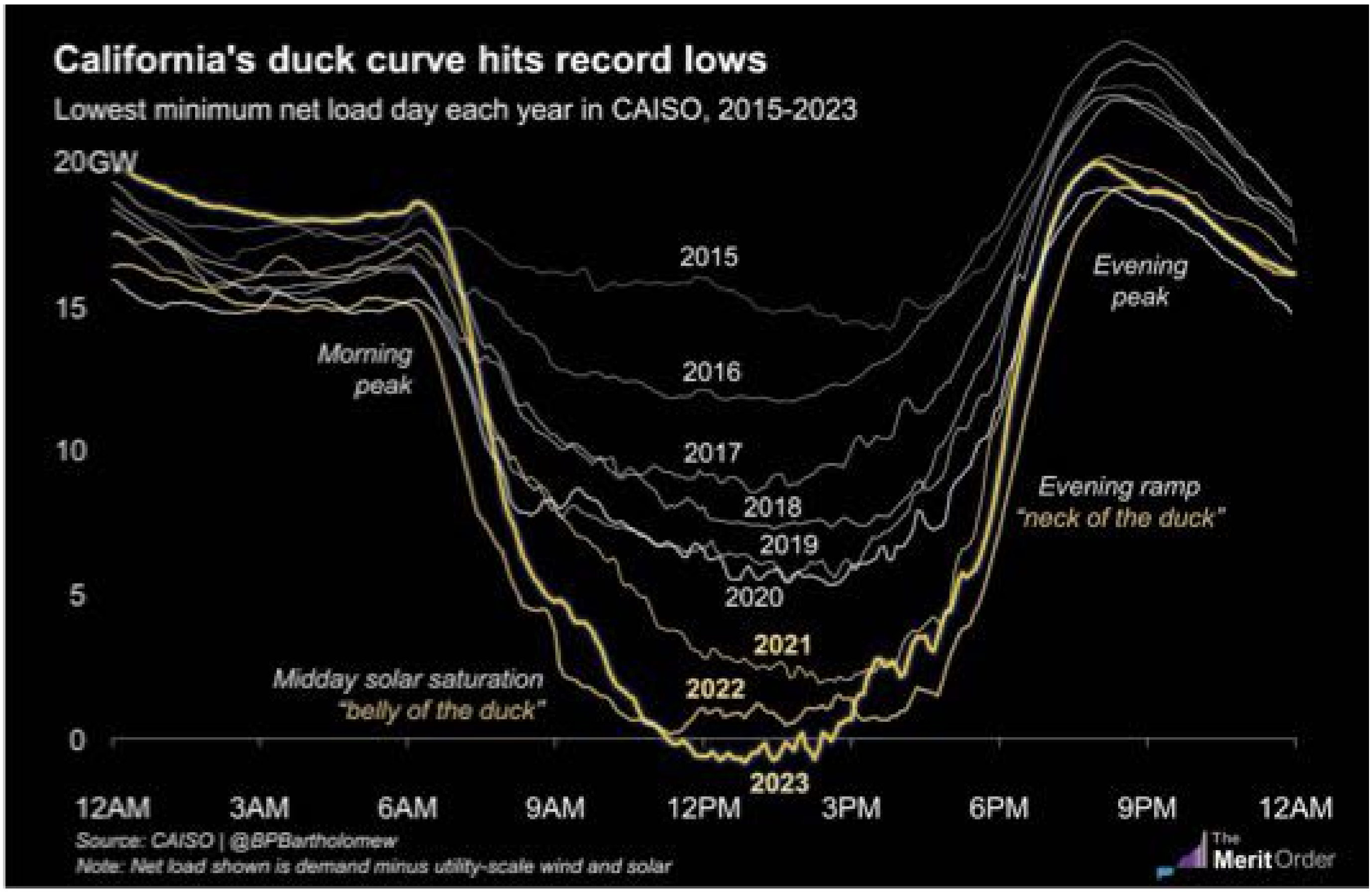
Grid Reliability, Economics, Security of Supply

Taiwan is an island, both physically as well as from an electricity system perspective. Most countries are a part of a larger grid, with transmission lines to neighboring countries. Taiwan does not. This has several implications. First, Taiwanese leaders cannot base their energy policy on the assumption that they will import electricity from their neighbors whenever they are in need. Taiwan needs to be 100% self-reliant 100% of the time.

While being a part of a larger electricity market has many benefits, it can also have some negative impacts. For example, if a large player in the market chooses to implement a bad or ideologically driven energy policy, its neighbors must also suffer the consequences. Smaller neighbors can even be overwhelmed by sudden surges of surplus production and, the next moment, face very high prices for their electricity as it is being exported to their bigger, wealthier neighbor in times of low wind and solar production and high demand. Leaders in well-connected countries can also avoid hard, unpopular, but responsible energy policy decisions by choosing to trust their neighboring countries to deliver. However, these neighbors might be making the same assumption.

The Roadmap chooses to replace reliable baseload power with a significant share of weather-dependent production like that from wind and solar. With an annual consumption of roughly 430 TWh/year in 2050, this implies an average demand of roughly 49 GW. This demand will vary depending on cycles such as day/night, week/weekend, and seasonal variation. Even minute-to-minute variations in wind and solar output can be significant and hard to forecast.

Solar power in good locations is quite reliably variable year-round. Production rises with the sun each day, and every night, it goes to zero. When the share of solar energy increases, this starts to cause some issues for the grid. The most well-known is the Duck Curve, shown in Figure XZ for California. California is used here as a case study of a very good location for solar energy that has also increased its share to significant levels.

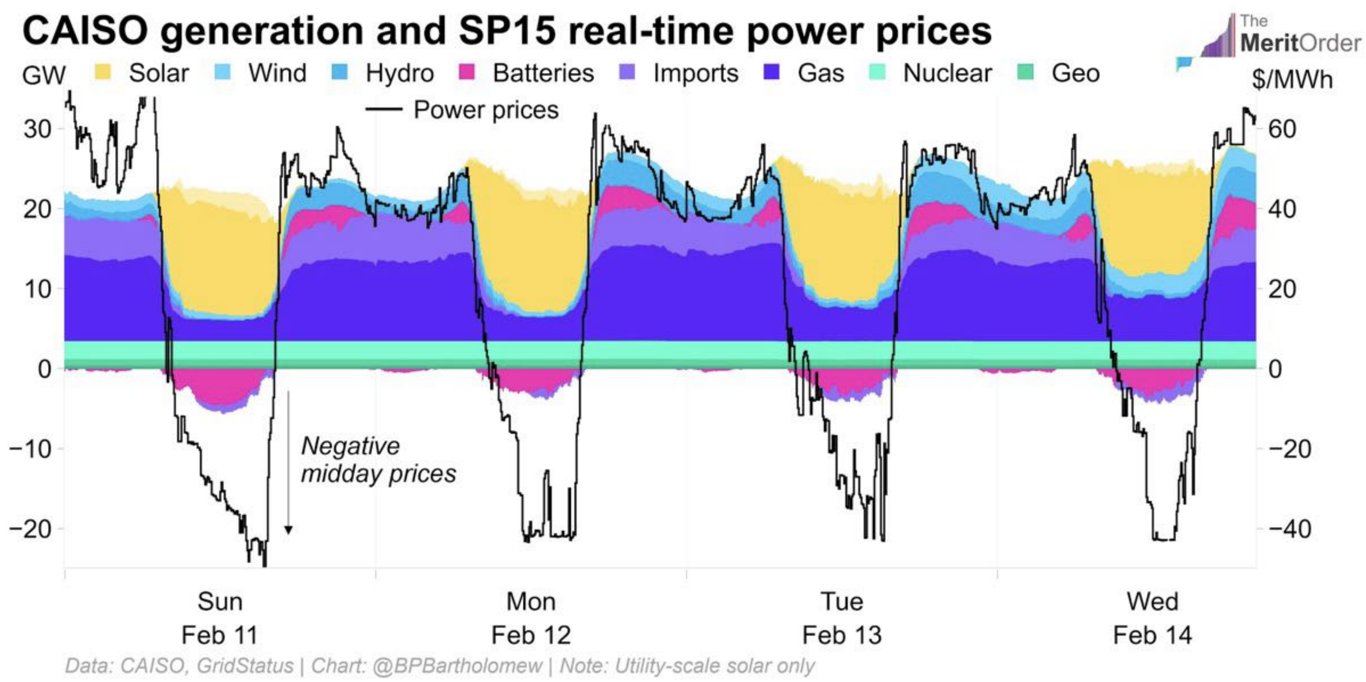


The duck curve shows the residual load remaining after solar (and in this case, wind) production. The steepness of this curve causes several problems. Perhaps the most serious one is the need for very rapid ramping of other electricity generation, both in the morning (ramp down) and evening (ramp back up). In 2022, the share of solar in California's total generation was 17%, while wind was at 11%. The installed capacities were roughly 17 GW and 6 GW, respectively.

solar
17%

wind
11%

With these installed capacities, the residual load decreased by almost 15 GW in just three hours, and then increased by 15 GW in three hours come early evening. This is managed mainly by natural gas (largest share), imports from neighboring states, batteries, and some hydro. Figure XZ shows these, as well as the impact on hourly prices. The market value of electricity fluctuates wildly, with hourly wholesale prices falling to as low as $-40/MWh midday and rising to as high as $60/MWh for the afternoon.



From a value perspective, solar panels are essentially producing a surplus of power with a "congestion fee" of up to $40/MWh placed for all power in the grid for that time. Given this, there is little incentive to invest in further solar installations, but certain policies, subsidies, and incentives can still push for even more investments. This also worsens the economics for other generation such as wind, geothermal, nuclear, and non-flexible natural gas turbines, but at least they can capture some positive value between afternoon and morning. Adding more storage is an obvious remedy as well, but it only makes economic sense if the owner gets to benefit from the price swings like those in California, which is currently not the situation in the Taiwanese grid.

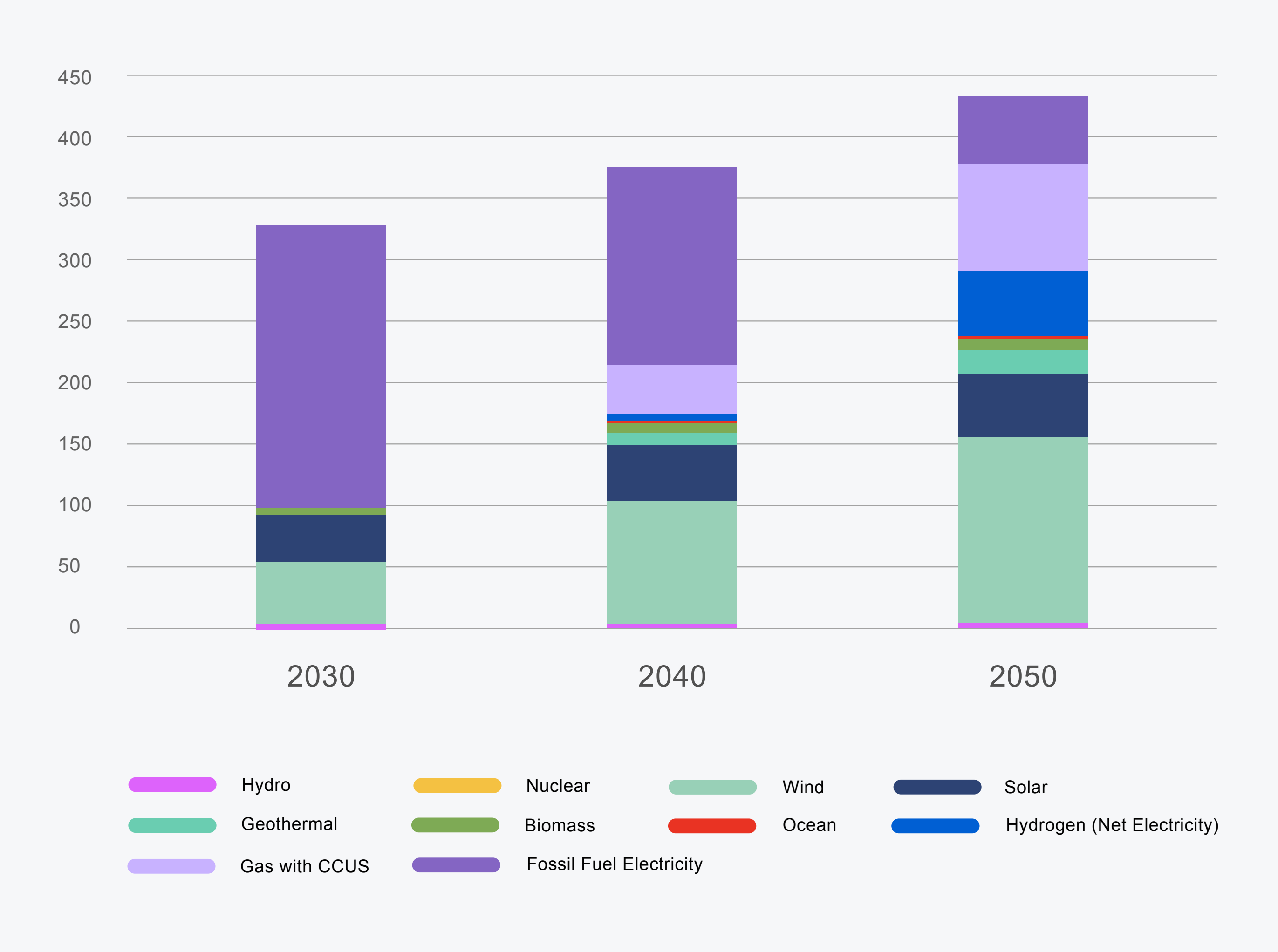
Taiwan's electricity market is regulated and has a single big operator, the state-owned Taiwan Power Company (Taipower), that produces and sells most of the country's electricity. A government-appointed board decides the prices that Taipower can charge its customers for electricity. This has led to a situation in which Taiwan has relatively low electricity prices but where the producer of said electricity consistently makes a significant loss. It must then either go deeper in debt (weakening its ability to invest in needed infrastructure) or ask its owner – the state – for a bailout.

In 2023, Taipower reported US$6.34 billion in losses. In 2022, the losses were even higher at $8.48 billion, or roughly $30/MWh of electricity generated in Taiwan. In short, electricity prices are kept artificially low with taxpayer support. This is not a sustainable way to run a power system, especially one that is in dire need of very large investments.

A regulated electricity market with stable electricity prices has some benefits, such as more capacity and incentives to invest in long-term projects and system-wide infrastructure such as transmission lines. But it also lacks some incentives that, for example, a spot market with hourly price discovery provides. Taiwan has FiTs for both solar panels and for batteries. From a grid management perspective, people and businesses are first paid to make the duck curve problem worse by offering a stable price for solar production that might have close to zero, or even negative, value when it is produced. This market signal is hidden, both due to regulated prices and to the FiTs, so it pays to install more solar no matter how much overproduction there would be when the sun is shining.

As for batteries, it is debatable whether the FiT for these is large enough to justify installations. In Figure ZZX above, the California grid shows a significant amount of battery capacity, but this is at least partly motivated by the extreme price changes that happen in the morning and evening and avoiding curtailment. Other motivations might be various subsidies given to installations, and protection from the increasing issues that the Californian grid is experiencing.

Taiwan Electricity Generation by Type in 2030 , 2040 and 2050 Low Case



In the Taiwanese context (see Figure CX), the share of wind and solar will be roughly 25% in 2030, 40% in 2040, and almost 50% in 2050, compared to California's 28% in 2022. If we take the average demand of 49 GW in 2050 with wind and solar both at 40 GW, the residual load can perhaps vary between 50 GW and minus 20 GW both in the morning and again in the evening. Ramping generation down and up at rates of up to 20 GW per hour places some extreme requirements on the rest of the system.

Taiwan cannot rely on imports or exports to stabilize the grid and has a smaller share of hydroelectric power compared to California. Natural gas with CCUS is also somewhat problematic. Carbon capture works best if it is operated on a power plant that produces constant baseload power, rather than ramping output up and down.

The cost for both electricity and CO2 capture on dispatchable generators is estimated to be very high.

A 2022 paper calculated these costs for small dispatchable generators in the UK :

1. Capital costs for a 10 MW open cycle gas turbine (OCGT) increased by 290%, from £6.53 million to £18.88 million ($8.3 to $24 million).

2. Levelized cost of electricity (LCOE) rose from £172-188/MWh without CCS ($218-$239) to £487-508/MWh with CCS ($618-$645).

3. The cost of CO2 avoidance was £448-470/tCO2 ($569-$597).

Regarding fossil fuel generation, a high share of variable renewable energy (VRE) leaves a high fossil fuel capacity, but with lower utilization of that capacity. This means that wind and solar act as essentially fuel-saving devices.

The energy transition also moves from coal generation to natural gas and hydrogen generation. While this is good for pollution and greenhouse gas emissions, it is bad for security of supply. Coal is easy and cheap to store in large quantities, while natural gas and hydrogen are much trickier. A constant stream of LNG and hydrogen/ammonia tankers is needed, as the storage at the LNG terminals is very limited. More import terminals for LNG (and later, hydrogen and ammonia) are also needed. The electricity grid would be relying on fuels for which only several days or a couple weeks of storage is available. This makes the whole system more prone to disruptions, whether man-made, accidental, or natural.

Summary of Low Case

There are several risks built into the assumptions of the Net-Zero Roadmap 2050 Low case. From a climate perspective, the assumption that annual carbon sinks will triple from 22 to 63 million metric tons of CO2/year by 2050 can be seen as risky. There is limited land in Taiwan to grow more forests, and the existing forests might start to slow their carbon sinks (growth) in the coming decades. Storing more carbon in agricultural soils can be done in several ways, but the easier ones might not be scalable or might store the carbon in a form that decomposes rather quickly. Carbon capture from industrial processes is a technical solution that can be scaled up rapidly, but it might also prove to be both expensive and demand a higher availability of clean, reliable energy. Ocean carbon removal also has a lot of unknowns.

The offshore wind deployment of 40 GW by 2050 is another big assumption that could be risky, for several reasons. Deployment is assumed to be handled by the global private industry, but at least for now, Taiwan does not appear to be an ideal place to invest in offshore wind farms. There is no longer a lucrative FiT from the government to guarantee a return on investment, and there are requirements for significant localization of the supply chain, which will increase development costs. It is unclear whether Taiwanese industry is willing to offer 20-year or longer power purchasing agreements (PPAs) with high enough prices to attract developers, and someone still needs to manage the variability of production. Further, there is the possibility that less than a third of the 40 GW that can be deployed on the seabed. If the rest needs to be deployed as floating offshore wind, the costs will grow even more.

From a grid stability perspective, Taiwan is assuming that it can manage an isolated grid with close to 50% of annual production coming from variable renewable sources, namely wind and solar. The combined capacity of these sources would be significantly higher than grid demand, leading to constant ramping of other production between zero and 100%. How this will be made viable in an island-grid is an open question, and something that no other country has managed to do, even with much lower shares of VRE.

Low Case Plus a Conservative Nuclear Program

Given the significant risks in the Low case scenario, what could Taiwan do to mitigate those risks and take some of the pressure off? The easiest approach would be to refurbish and restart the current nuclear reactors that have either been closed (4 reactors) or face closure by 2025 (2 reactors) and to complete and start up those that have not quite finished construction (2 reactors). This scenario looks at how this program would affect the wider Net-Zero Roadmap 2050 Low case, while holding everything else the same regarding clean energy deployment and demand growth.

Nuclear Program for Taiwan

How could a nuclear program for Taiwan proceed? At the moment, the target is to close down all nuclear plants by 2025, and most units have already been shut down – although irreversible decommissioning has not started due to various factors. This means that it will take some time and effort to bring the units back online, but that it will be feasible and relatively low cost to do so. Our program for the scenario assumes that the decision to cancel the phaseout is made in 2024 or 2025, and therefore at least one plant will stay operational at any given time.

Declaring such a program will start several chains of action, and bring certainty to the nuclear sector to enable very significant investments in the coming years and decades.

A thorough maintenance, refurbishment, and a power uprate program (uprate means increasing the maximum output of a reactor) for the existing reactors needs to be planned and executed, along with lifetime extensions from 40 to 60 years, with an eye to a further extension to 80 years. Fuel contracts need to be renewed and start-up fuel deliveries ordered as necessary. Interim storage facilities for spent fuel need to be expanded or new ones licensed and built. These will all take significant time, so the sooner they are initiated, the earlier the plants can get back online.

The six units that have operated have a combined capacity of around 5 GW and output record of roughly 42 TWh/year. They will be brought back online after thorough maintenance, refurbishment, and possible power uprates. In the scenario, the annual nuclear generation dips to around 10 TWh/year from 2024 to 2026. After that, the scenario assumes another reactor coming online roughly every 18 months and adding on an average 5 TWh of annual production each year. This continues until all six reactors are fully back online in 2033, producing 45 TWh of electricity annually.

Meanwhile, preparations to finish the construction of Lungmen units 1 and 2 are made, and operator training started. Lungmen unit 1 comes online in 2034-2035 and unit 2 in 2036-2037, adding another 20 TWh of generation. This would bring total nuclear generation to 65 TWh by 2037 with roughly 8 GW of capacity. Although a lot of work and investment needs to be made, this is a relatively straightforward way to add clean and reliable power generation to the Taiwanese grid. Long-term operation of nuclear plants is, according to the IEA, among the most cost-effective ways to add clean electricity production, costing less than US$55/MWh. It is no wonder that the IEA recommends that countries seek to extend the operations of their nuclear fleets whenever it is safe to do so.

This program would secure a future for the nuclear industry in Taiwan, keep and expand the expertise in nuclear technologies, and also prepare Taiwan for future nuclear technologies and new-build projects if needed (see later scenarios for more). It is extremely costly and hard to start building this expertise from scratch once it is lost.

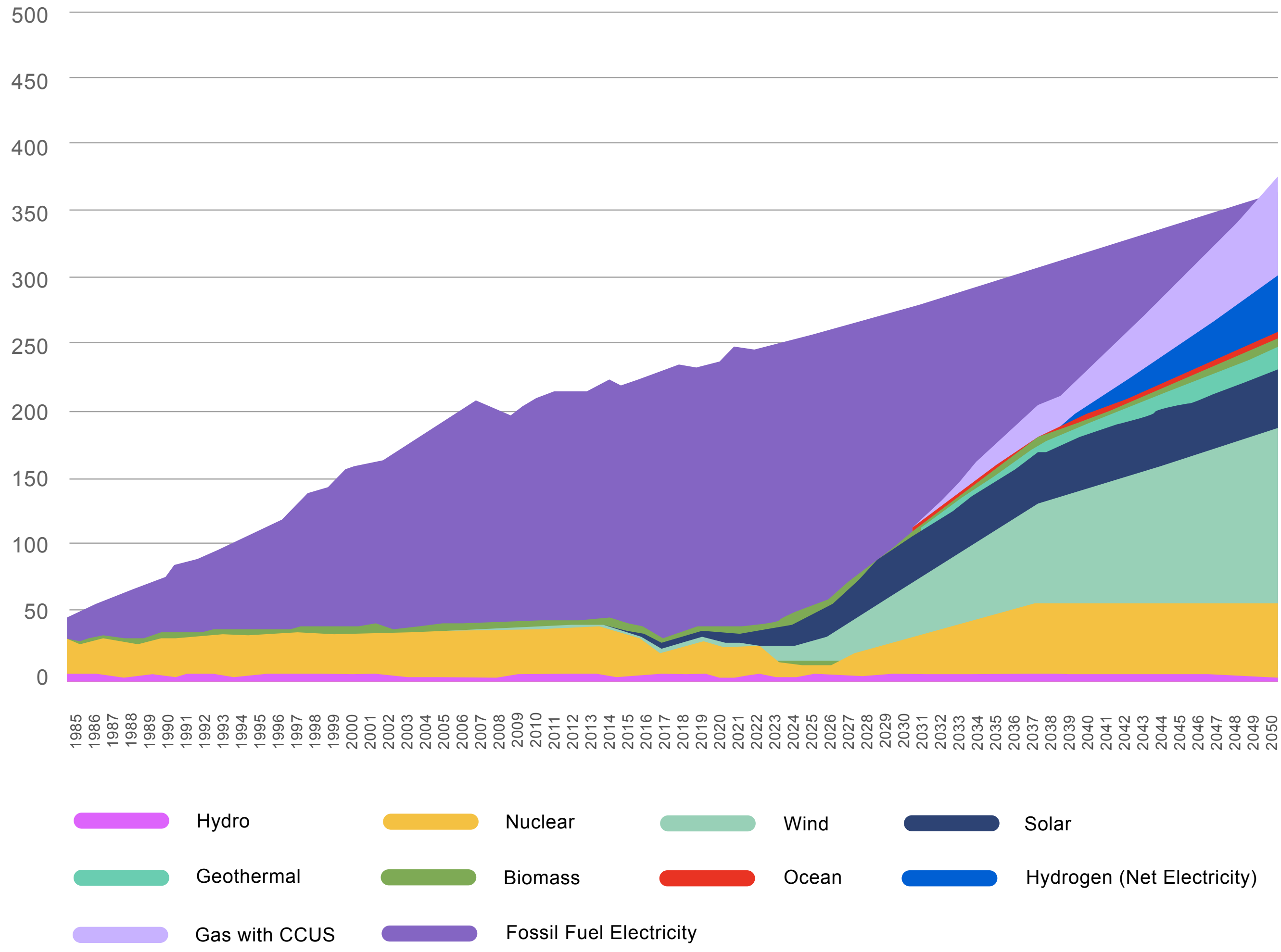
Discussion on Low Case Plus Nuclear Program -Scenario

As shown in Figure ZX, the 65 TWh of nuclear production is enough to remove unabated fossil fuel electricity generation completely before 2050.

Nuclear would also reduce the cumulative emissions of the electricity sector by 650 million metric tons between 2025 and 2050 ,

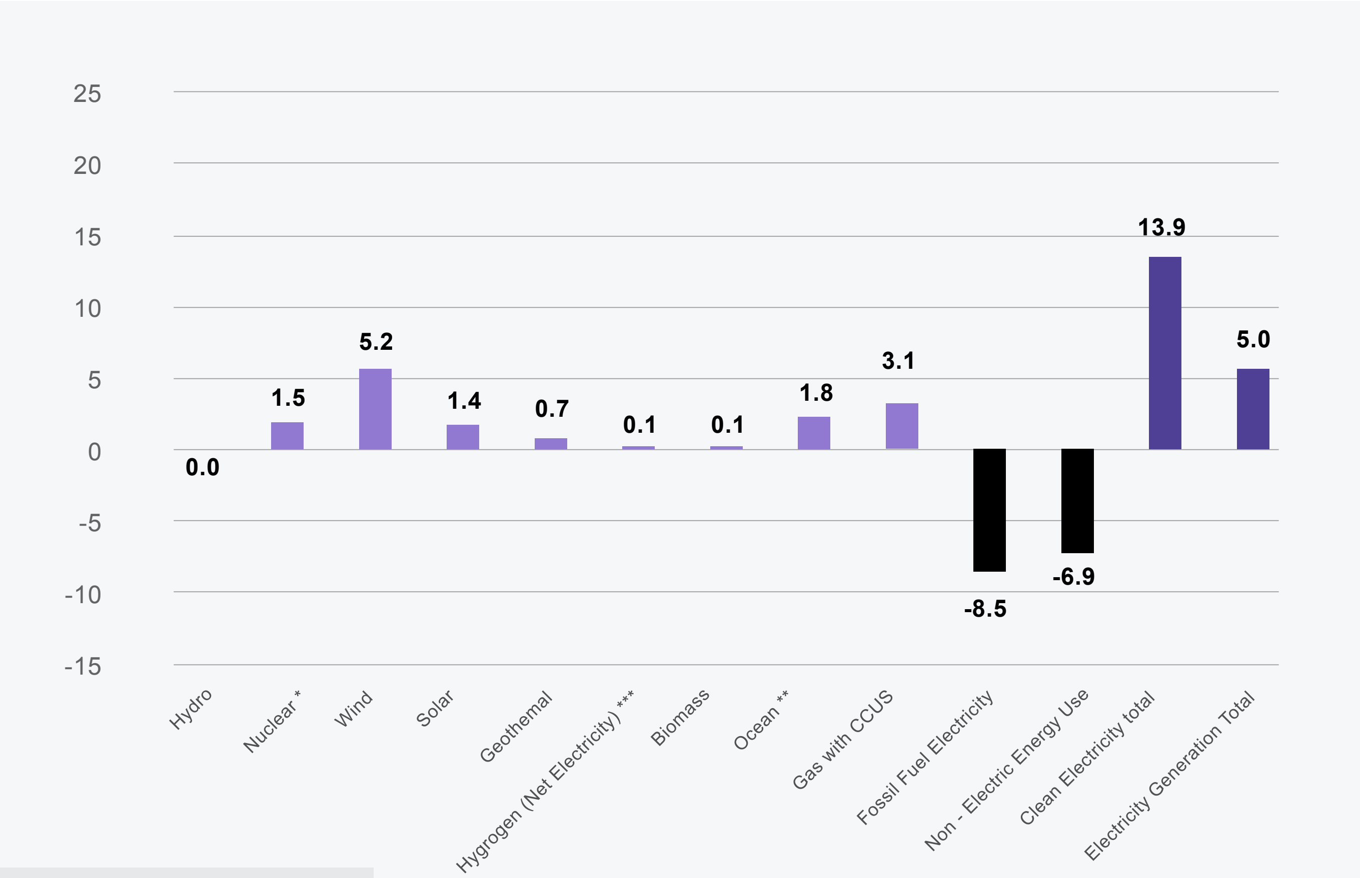
assuming it would produce 1,295 TWh during that time and replace generation with emissions of 502 gCO2/kWh on average.

Taiwan's Historic and Projected Electrcity Genration by Sourse Net - Zero 2050 Roadmap , Low case



Having a baseload of 8 GW of clean capacity that can be brought back online with relatively small deployment risks and at a low cost can greatly mitigate some of the risks identified in the Low case scenario. The goal of net zero emissions by 2050 is best viewed not as a binary case of either success or failure. Having the nuclear fleet operational will improve results related to emissions reductions and pretty much any other relevant metric. But adding the nuclear program to the Roadmap is not an excuse to not also move forward on the other pieces of the puzzle. Figure ZX shows the annual average changes in energy consumption by source.

Auunal Average Change in Energy Use by Source 2022 - 2050 - Low Case + Nuclear



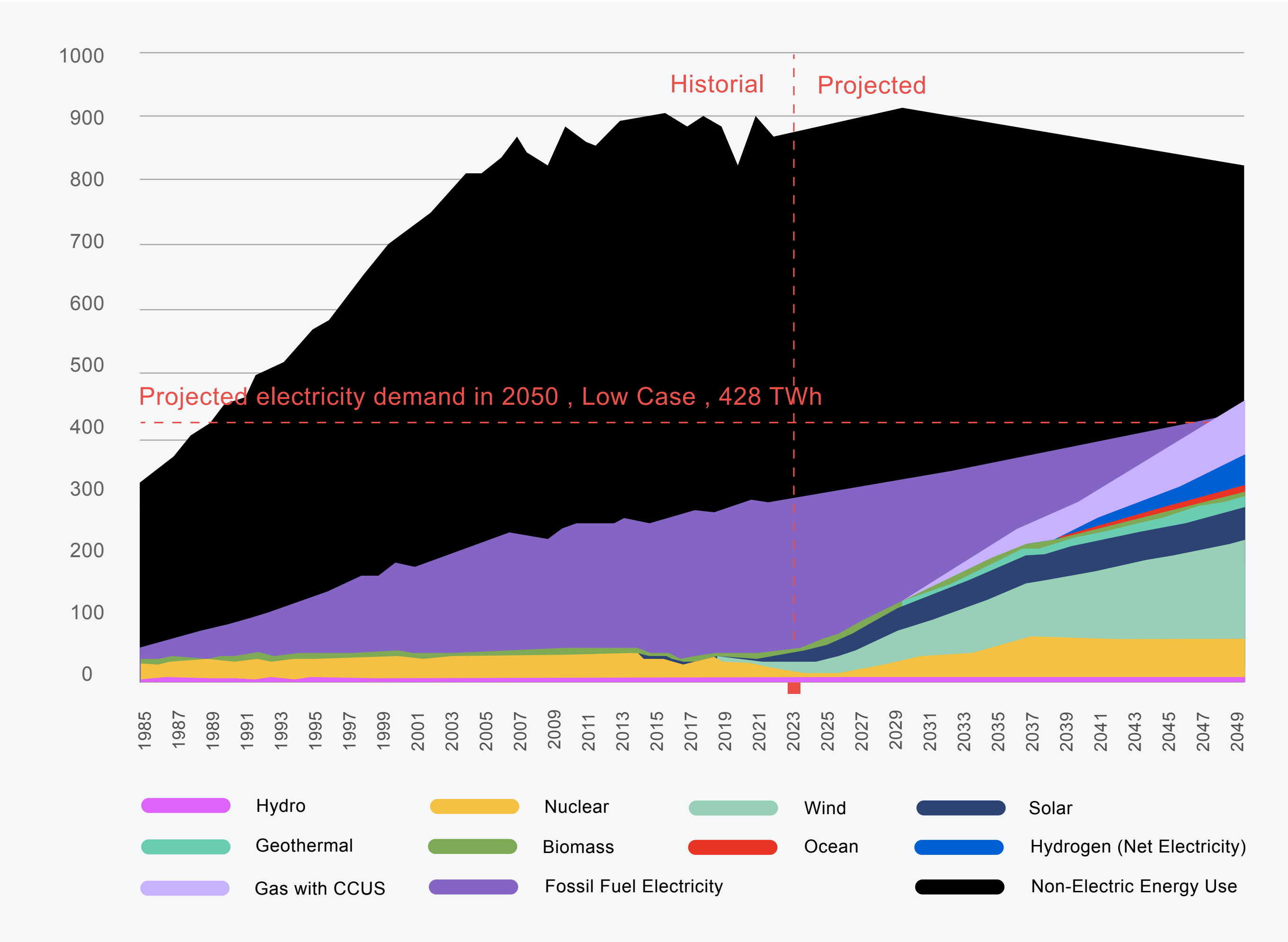
* Phase-out by 2025.
** Deployment starts in 2031.
*** Deployment starts in 2039.

As we can see in Figure ZX below, roughly half of the final energy use remains, and this will be covered mostly by fossil fuels. As is the case in the Low case without nuclear, these emissions need to be dealt with through carbon sinks and capture. But with nuclear up and running, there will be much less of these emissions to deal with. If nuclear replaces electricity with average emissions of 502 gCO2/kWh, then

65 TWh/year of nuclear production reduces CO2 emissions by 32.5 million metric tons per year.

This is 1.5 times the estimated carbon sinks of Taiwan in 2020.

Total End Energy Use, Historical and Forecast Net - Zero Roadmap,Low Case + Nuclear Program



Nuclear energy acts mostly as baseload capacity, similar to coal plants. It would first replace coal generation and then combined cycle natural gas production, for which ramping production up or down is slower than with open cycle gas turbines.

Grid Reliability, Economics, Security of Supply

As discussed in the Low case scenario, grid reliability will be an issue, with close to half of annual energy being produced with variable renewables. Having an additional 8 GW of stable, reliable power production reduces the need to have other capacity ready on standby when the sun sets and the wind dies down. Having reliable capacity available increases grid stability and decreases the costs needed to keep it stable.

The non-fossil sources of baseload energy include geothermal (3 GW), biomass (1.4 GW), and ocean energy (1.3 GW). Nuclear would more than double this capacity, making grid reliability and the Duck Curve much easier to manage. There is also a projection to have enough hydrogen to produce 12% of total electricity and natural gas with CCUS to produce 20% of total electricity. Publicly available materials on the Roadmap don't disclose the amount of capacity for these two energy sources. As a thought experiment, let's say they were to be operated at 25% and 50% CFs, respectively. This would mean that hydrogen would be used for peak power and rapid ramp-up needs, while natural gas would be used for load following and some baseload. In this case, hydrogen would need to have an installed capacity of 23 GW and natural gas one of 19.5 GW, for a total of 42.5 GW. This is almost as much as the average demand for the grid in 2050.

With additional capacity available, there would be even more overproduction when the sun shines and the wind blows – unless nuclear power could replace another source of electricity with a similar enough function in the grid, such as coal power or combined cycle gas turbines. This, however, is not the fault of nuclear as such, but a feature of wind and solar when their shares become higher. These can be curtailed or stored, but it requires incentives. If there is a PPA or a FiT in place that guarantees a price for all production, even when there is overproduction in the grid, it eventually becomes a systemic problem that needs to be managed and that has a cost.

INFOBOX: Flexible Nuclear?

Nuclear power plants can also be curtailed, as current generation plants are designed to do at least some degree of load following if needed. Load following means ramping the power up and down as needed to keep supply and demand in balance. This does not save much on fuel costs (which are already a very small part of the total cost) and can actually increase the need for additional maintenance. Yet, France uses its nuclear fleet in load-following mode as part of normal operations, and even the German fleet did this when it was operational. The Finnish nuclear fleet has also started ramping their production down when electricity spot prices go negative for longer times, and part of the fleet of wind turbines (those that get their income from selling power to the spot market) have also curtailed their production due to negative pricing.

Extending the operations of nuclear plants is among the most cost-effective ways to add clean energy production. It also provides the system with valuable services such as spinning reserves to help with frequency control and reduces the need for other investments into these auxiliary services, leading to significant reductions in the overall costs of running the electricity system. This would be especially valuable in Taiwan's situation, where the state-owned utility Taipower is already struggling financially but does not have the mandate to increase electricity costs by itself.

Finally, having nuclear power as part of the grid would also improve the security of supply. While nuclear fuel is imported like the majority of fossil fuels, it is physically easy to store, takes little space, and is relatively cheap. Therefore, nuclear power plants can (and often do) store years of fuel supply at the site which improves the security of supply significantly. There is also many years' worth of fuel in the operating reactor.

Summary on Low Case + Nuclear

2025 - 2050

650 Million

2037

30+ Million

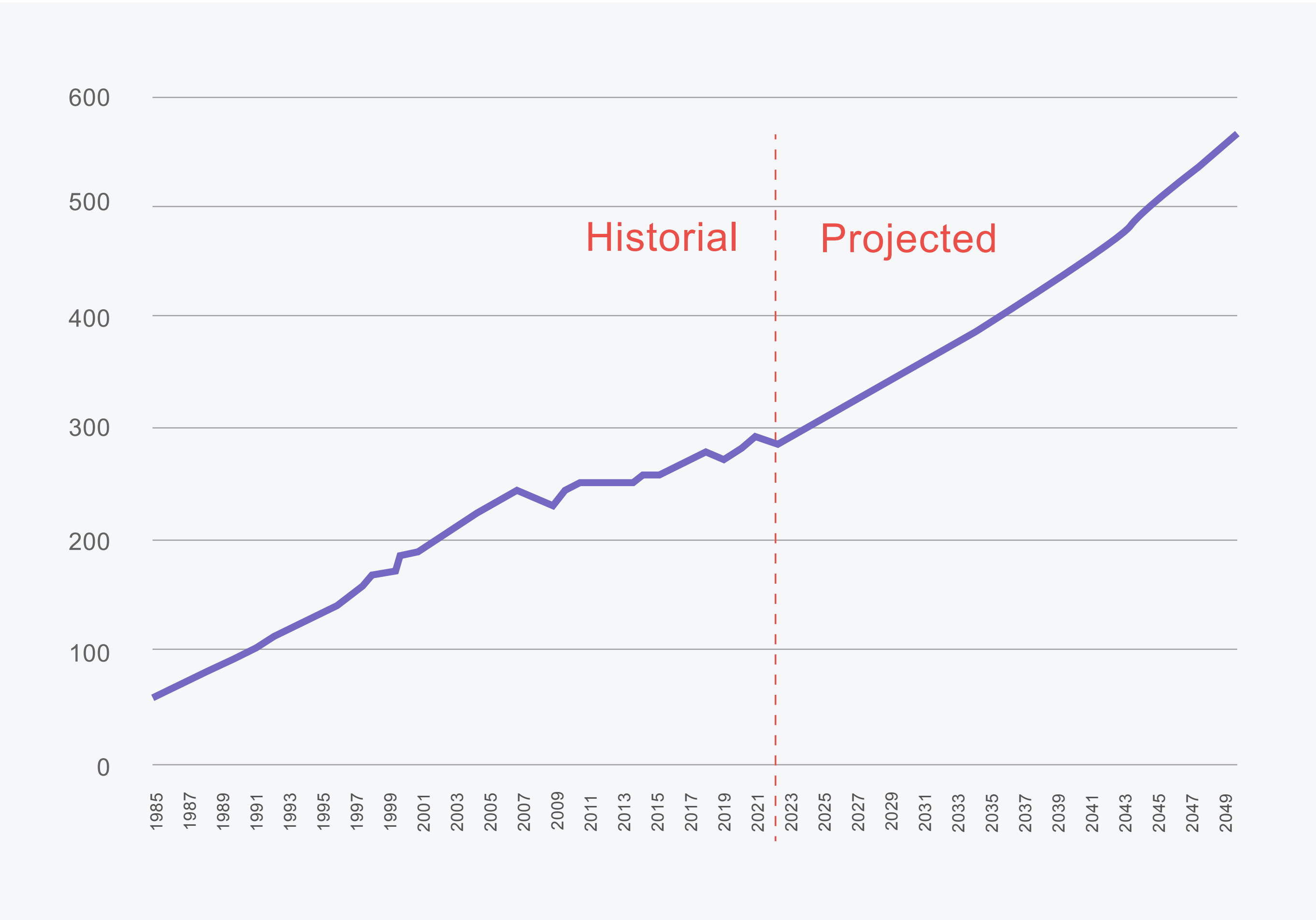
Restarting the Taiwanese nuclear fleet would make sense in almost every regard, although the costs of the program need to be estimated in more detail and the question of additional interim storage for spent fuel addressed, as the current facilities are filling up. It is among the lowest cost to add clean energy production. It offers the grid valuable services and reduces its volatility. It replaces the rest of the unabated coal and natural gas use from the electricity mix, saving cumulatively some 650 million metric tons of CO2 emissions between 2025 and 2050, and 30+ million metric tons annually when the fleet is fully operational around 2037 forwards.

Having the nuclear fleet refurbished, uprated, and restarted would also ensure Taiwan's nuclear expertise, which is now at risk of disappearing. Rebuilding this expertise is very expensive and time consuming if Taiwan at some point wants to deploy new nuclear technologies such as small modular reactors (SMRs) and other advanced reactors. These are mostly not commercially available at the moment (although neither is ocean energy) but could provide very low-cost clean electricity and industrial heat at large scale in the future. It would make sense for Taiwan to hedge its bets and maintain its nuclear sector so that it can deploy these technologies if they fulfill their promises and potential in the coming years.

High Case

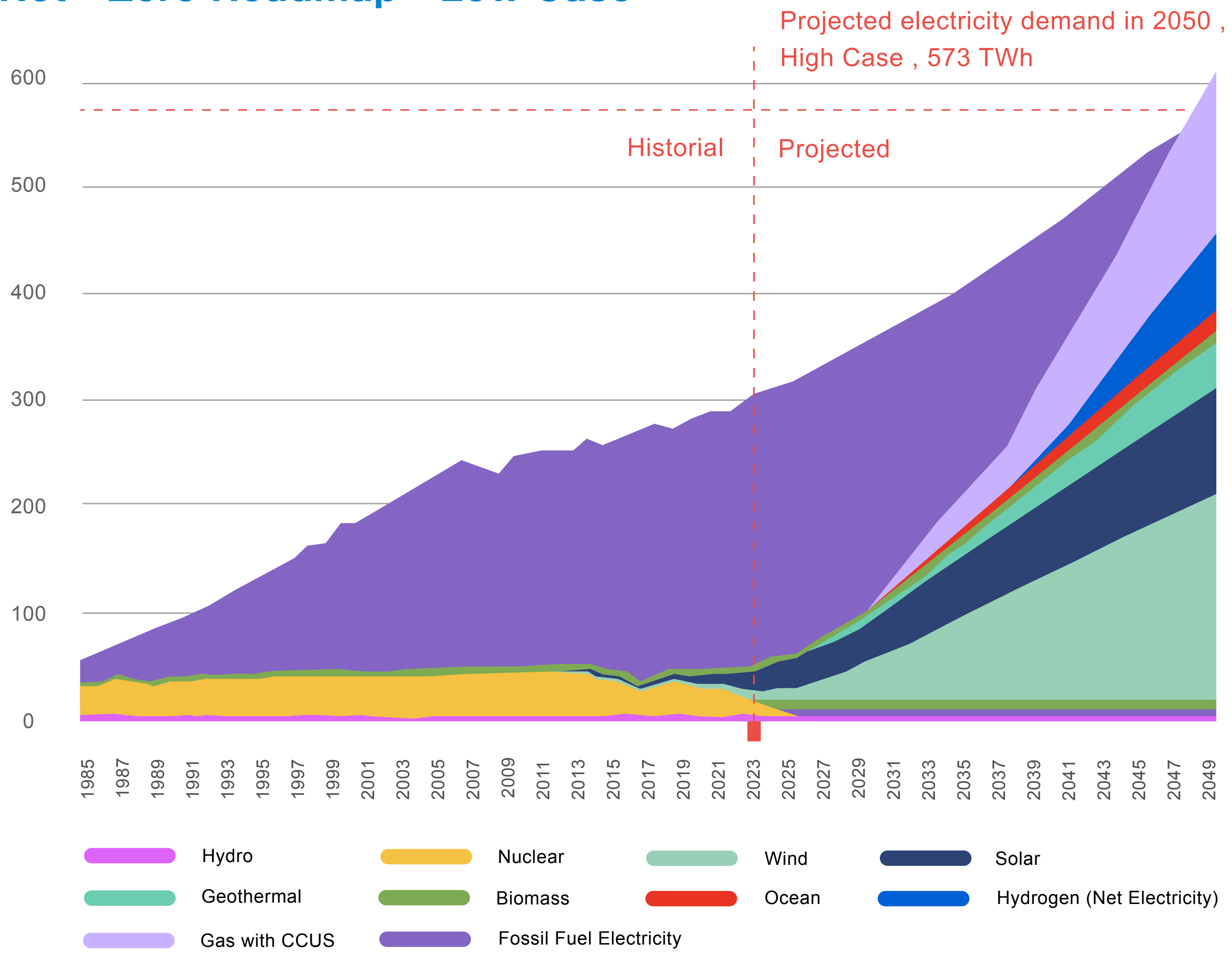
The High case taken from the Roadmap assumes the higher end of the range both for clean energy deployment and for demand growth. Electricity demand will rise to 573 TWh/year in 2050, showing robust 2.5% annual growth, see Figure ZX.

Taiwan's Historic and Projected Electricity Generation Net - Zero 2050 Roadmap , Low case



To meet that growing demand, each of the clean electricity sources ramps up even faster than in the Low case scenario. Figure XC below shows this deployment for each individual energy source, as well as the decrease in unabated fossil fuel generation. The growth rates are again extrapolated from publicly available Roadmap materials, and each of the energy sources is briefly discussed below.

Taiwan - Shared of Energy Sources in Electricity Generation Net - Zero Roadmap - Low Case



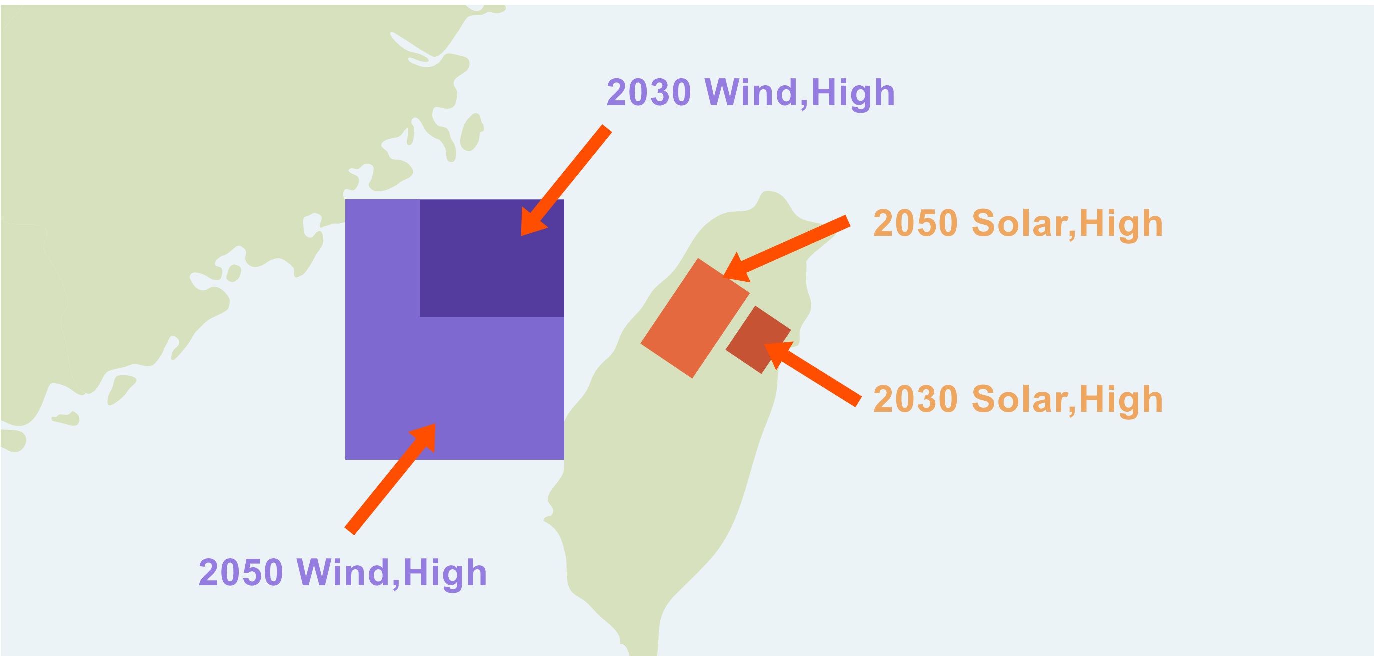
High Case - Offshore Wind

In the High case scenario, offshore wind grows to 55 GW by 2050. The target for 2030 is the same as in the Low case, at 13.1 GW and 1,440 MW of annual installed capacity between 2023 and 2030. Between 2031 and 2050, annual installations average 2,095 megawatts. This implied annual average rate of increase is over 1.3 times Taiwan's total installed wind capacity in 2022.

As in the Low case, some experts say that there is only space for ~12 GW of seabed-installed offshore wind around Taiwan. This means that the rest—43 GW—would need to be installed as floating offshore wind, which is much more expensive. According to the roadmap, offshore wind will produce 206 TWh of electricity in 2050, 36% of total consumption.

High Case - Solar PV

Solar, in the High case, sees a significant change. The installed capacity in 2030 is 31 GW, the same as in the Low case. For 2050, however, the installed capacity will grow to 80 GW, compared to 40 GW in the Low case. This will produce 100 TWh of electricity, 17.5% of total consumption. Figure ZX shows the land and sea requirements for the High case for wind and solar.



High Case - Other Domestic (Biomass, Geothermal, Ocean)

The High case accelerates the ramp-up of geothermal, ocean energy, and, to a lesser degree, biomass energy. Geothermal capacity grows to 192 megawatts by 2030, and then accelerates growth significantly to 300 MW per year, ending up at 6,200 MW in 2050, and producing 40 TWh of electricity. Ocean energy starts growing only after 2030, adding 375 MW per year to a total capacity of 7,500 MW by 2050, producing 19 TWh of energy. This is a lot to expect from an energy source that is not widely deployed anywhere. Biomass grows only modestly, from the current level of ~800 MW to 1,800 MW by 2050, producing 11 TWh of energy.

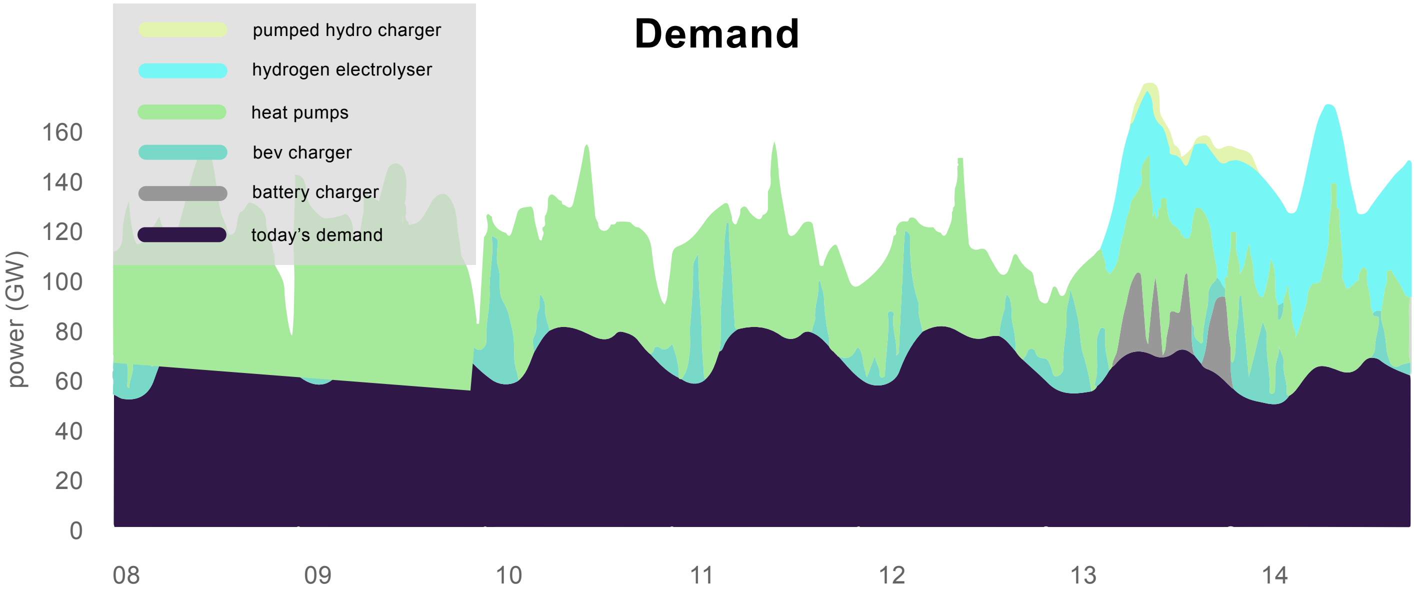
High Case - Imported: Hydrogen

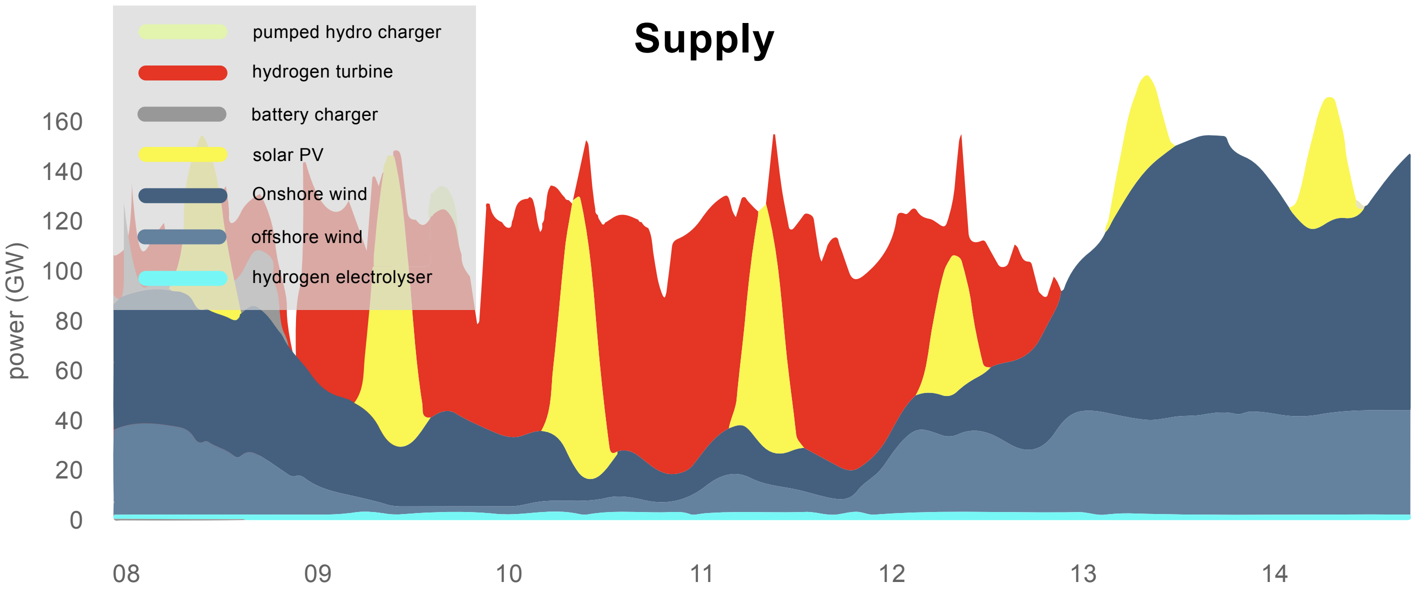
The High case assumes around 69 TWh of electricity production in 2050, or 12% of the total electricity generation. Our scenario assumes that the share of hydrogen starts to grow by 1% of total electricity generation each year, starting in 2039. This contrasts the 55 TWh of imported hydrogen in the Low case but has largely the same issues.

The hydrogen needs to be manufactured somewhere, a place that has a significant surplus clean electricity production. It needs to be transported to Taiwan, either as hydrogen or as ammonia, and then stored in significant quantities (millions of metric tons). We estimate that the main use case for hydrogen turbines or fuel cells is to manage the duck curve, or the rapid need for additional capacity every evening as the sun starts to set and demand ramps up as people return to home and start preparing dinner and turn on their air conditioning.

A recent modeling exercise from Germany enlightens the various problems. As seen in Figure ZX, Germany would occasionally need roughly 90 GW of hydrogen generation capacity on a grid that has a winter demand of roughly 100 to 140 GW.

Week 2024-2





The annual hydrogen generation would be around 100 TWh, which means that the 90 GW of hydrogen turbines would run at an average CF of only 13%, essentially as backup and peaker plants, which stand by to offer production on short notice when it's needed. This would mean high costs for the fuel, storage, and for the capex and fixed opex. It's therefore reasonable to ask who would pay for that high cost of electricity, and who would pay for the investments for the needed infrastructure.

The figure also shows that Germany would be making at least some of its own hydrogen. There seems to be roughly 40 GW of electrolyzer capacity coming online as the wind picks up, but it only runs when there is overproduction of electricity. It is safe to assume that the CF of the electrolyzers is quite low, leading to higher costs for hydrogen due to high capex and fixed opex. They might operate at higher capacity in the summer when more solar is available, but storing potentially ten million metric tons of hydrogen for seasonal variation is also very expensive and difficult.

The modeled German grid is roughly two times larger than the projected Taiwanese grid for the High case at an average load of 65 GW in 2050.

High Case - Imported: Natural Gas with CCUS

Starting in 2031, the High case scenario sees steadily increasing electricity generation from natural gas with carbon capture and utilization or storage (CCUS). It starts at 1.35% of total electricity generation in 2031 and increases by 1.35 percentage point each year after that, reaching a 27% share in 2050, or 155 TWh. As is the case with normal natural gas in Taiwan today, it is imported as LNG. The issues are similar (lifecycle emissions, difficulties and costs in carbon capture and storage etc), but bigger, than in the Low case.

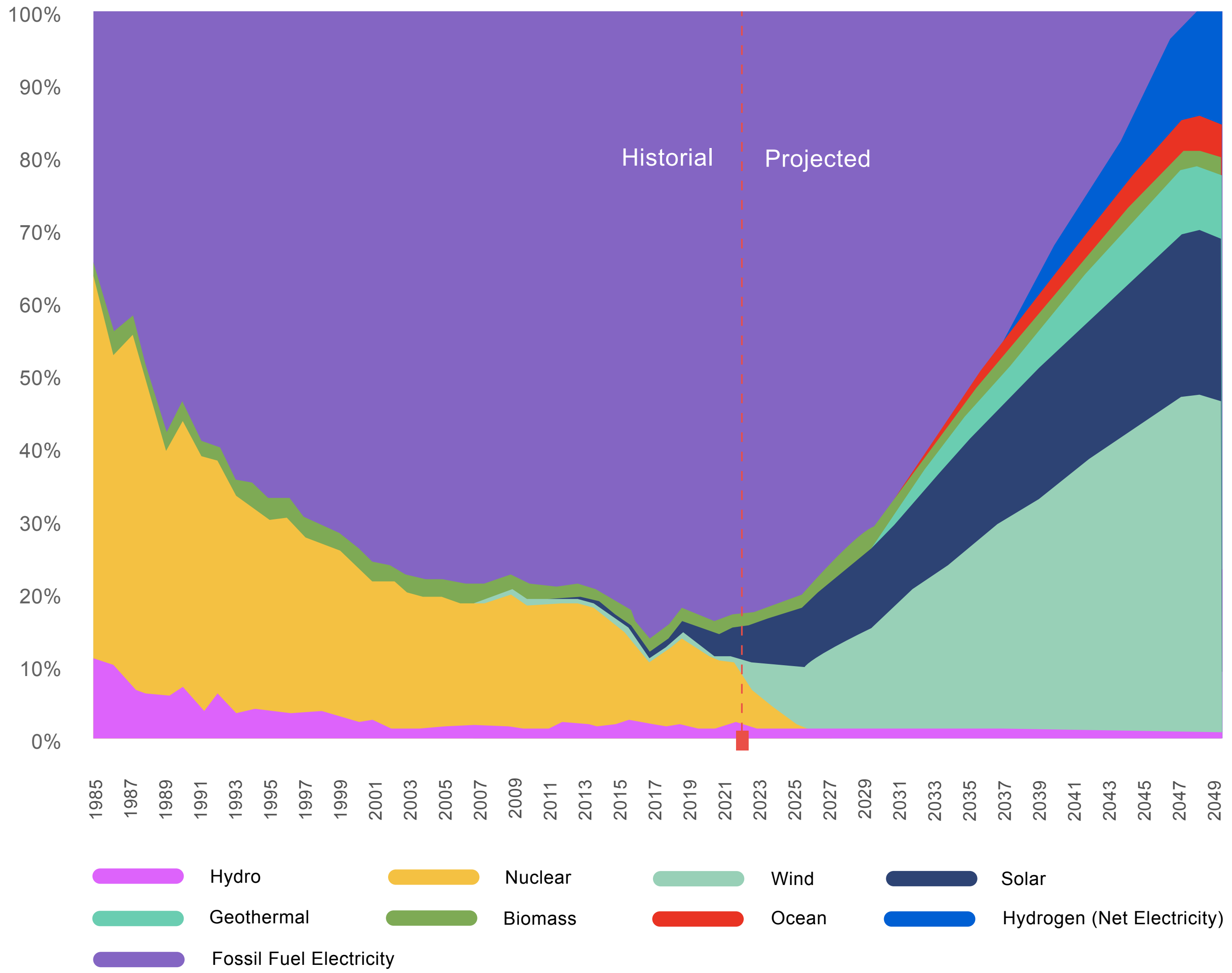
Given the very large share of wind and solar even the Low case scenario has, it is likely that a significant share of natural gas electricity generation would be used for flexible load following (i.e., with simpler open cycle turbines instead of combined cycle turbines). It remains a question how possible it will be to perform carbon capture efficiently if the production is constantly ramped up and down. The 128gCO2/kWh taken from the UNECE report might be on the lower end, as it is a number given for combined cycle use, which is effectively operated as baseload or close to it.

Finally, the captured carbon must somehow be stored (or used). The carbon intensity of natural gas turbines depends on the turbine type (open cycle or combined cycle) and how they are operated (ramping up and down increases emissions and leaks). Assuming 400 gCO2/KWh on average, the 155 TWh of electricity production will also produce 62 million metric tons of CO2 that needs to be captured and stored (or used) each year. Given that the capture of carbon is perhaps 90% efficient, the amount of CO2 that needs to be stored is a bit less than that, perhaps closer to 55 million metric tons.

Fossil Fuel Generation

The High case projects unabated fossil fuel electricity to fall to zero around 2049. Figure CV shows the historical and projected shares of electricity generation sources.

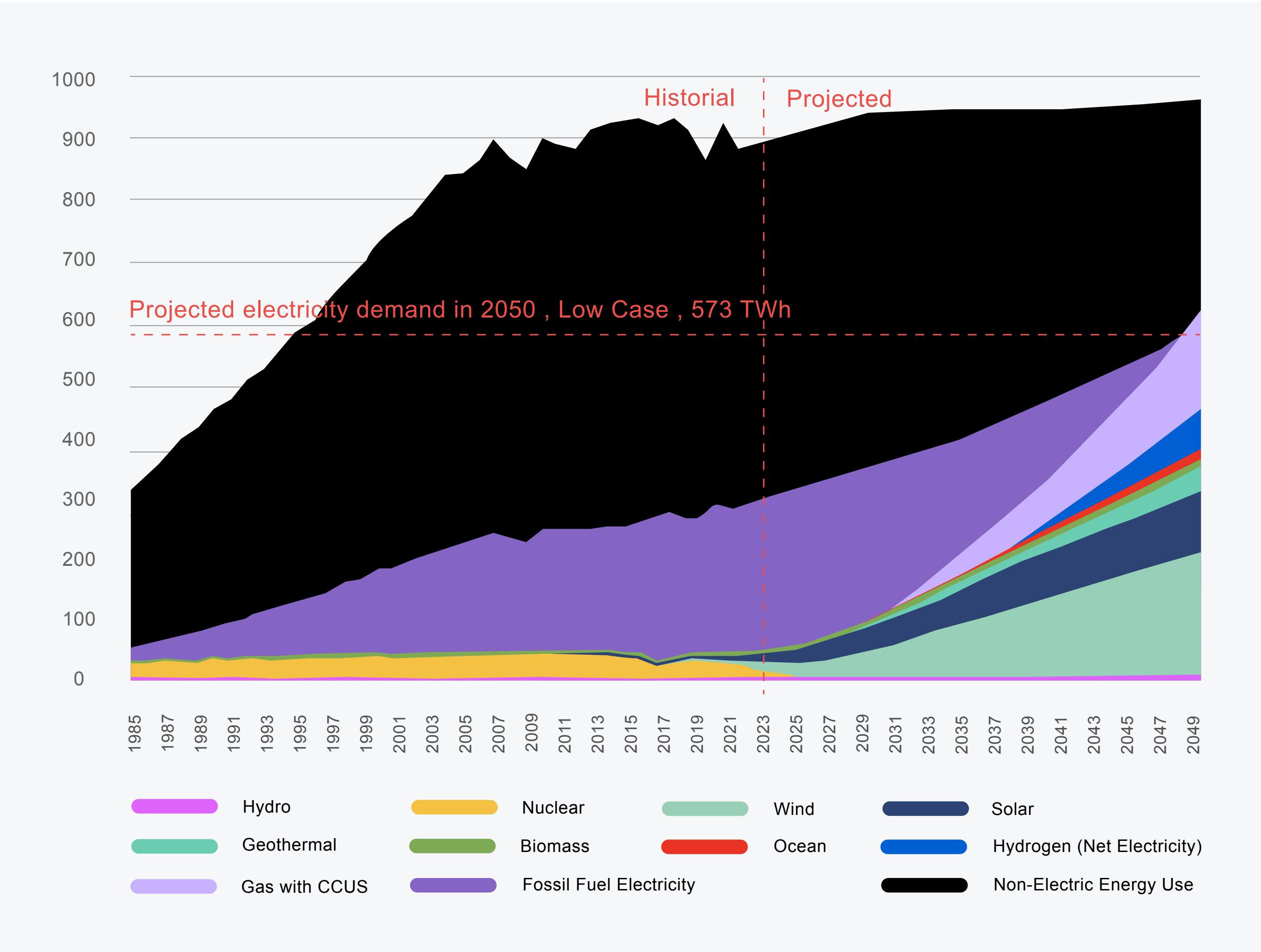
Taiwan - Shared of Energy Sources in Electricity Generation - High Case



Fossil Fuel Generation

In the High case scenario, total final energy consumption is projected to grow by 8% until 2030, and 1% after that until 2050.

Total End Energy Use, Historical and Forecast
Net - Zero Roadmap,Low Case + Nuclear Program



The High case reaches a 61% share for electricity for final energy use. Non-electric energy use is at 342 TWh. Assuming that is fossil fuels with average emissions of 200gCO_2/kWh, 68.4 million metric tons of CO_2 emissions remain. Note that the 200 grams is an estimate, and it is lower than the 502 grams used for electricity because these fuels are used directly for energy (heat, mobility), not for generating electricity which incurs losses and therefore has higher emissions per unit of final energy consumed.

This 68.4 million metric tons is reasonably close to the projected carbon sinks of ~63 million metric tons by 2050, and the difference can be due to variations in estimates and the CO_2/kWh used in final energy use. On top of this, some 55 million metric tons of CO_2 will need to be captured and stored/used from electricity generation with natural gas.

Discussion on High Case Scenario

If the deployment rates for clean electricity were ambitious in the Low case scenario, they are even more so in the High case. There will be 37.5% more offshore wind by 2050 (55 GW), and 100% more solar PV (80 GW) in the High case compared to the Low case. Geothermal projection for 2050 increases by 107% and ocean energy by 475% between the High and Low cases. Wind and solar alone would supply more than half (206 TWh or 36% of wind and 100 TWh or 17.5% of solar) of the total annual electricity demand of 573 TWh.

This means that all the deployment risks and bottlenecks of the Low case scenario are much more pronounced in the High case. However, the High case projections do manage to decarbonize the electricity generation by 2050, if those risks and issues can be overcome. To be clear, the Low and High cases discussed here are just the lower and upper bounds of the official Roadmap.

Grid Reliability, Economics, Security of Supply

The High case has higher overall electricity demand growth, but also higher growth for variable renewable electricity (VRE). The average grid load in 2050 is around 65 GW. VRE sources, namely wind (55 GW) and solar (80GW), are roughly double that in combined capacity. Solar alone can produce more than the whole grid can use on a sunny day. If there is both wind and sun available at the same time, there can be tens of gigawatts of overproduction from these two alone.

Daily solar production changes can cause extreme issues for grid management, as solar output can grow from zero to more than the grid demands in just a few hours, and then drop back to zero again while demand increases in the afternoon/evening. If wind production happens to move in the same direction, increasing in the morning or dying down in the evening, grid management will be even harder, with potential residual load decreasing or increasing at rates of 10-20 GW per hour. This is a very substantial issue to be dealt with.

Finding someone to invest in such a system will be very hard, at least without clear subsidies and mechanisms to mitigate the risks. If FiTs or annual PPA contracts are used, the producers get paid for their product no matter how much surplus production there is in the grid at any given moment. This means that they have no incentive to curtail their production even when handling the excess production becomes very expensive. In such a situation, Taipower (and eventually the taxpayer, since Taipower is state-owned), would need to spend significant sums to “take care of the waste” (overproduction) while at the same time it, or someone else, would be paying handsomely for the producers to keep producing at the maximum rate.

Unless dozens of gigawatts of grid batteries, electrolyzers and hydrogen fuel cells, or turbines and hydrogen storage facilities are invested in and the grid expanded and strengthened significantly, it seems unlikely that it would remain reliable under such rapidly changing loads. These investments would significantly increase the total system cost of providing reliable electricity.

Summary of High Case

The High case has higher overall electricity demand growth, but also higher growth for variable renewable electricity (VRE). The average grid load in 2050 is around 65 GW. VRE sources, namely wind (55 GW) and solar (80GW), are roughly double that in combined capacity. Solar alone can produce more than the whole grid can use on a sunny day. If there is both wind and sun available at the same time, there can be tens of gigawatts of overproduction from these two alone.

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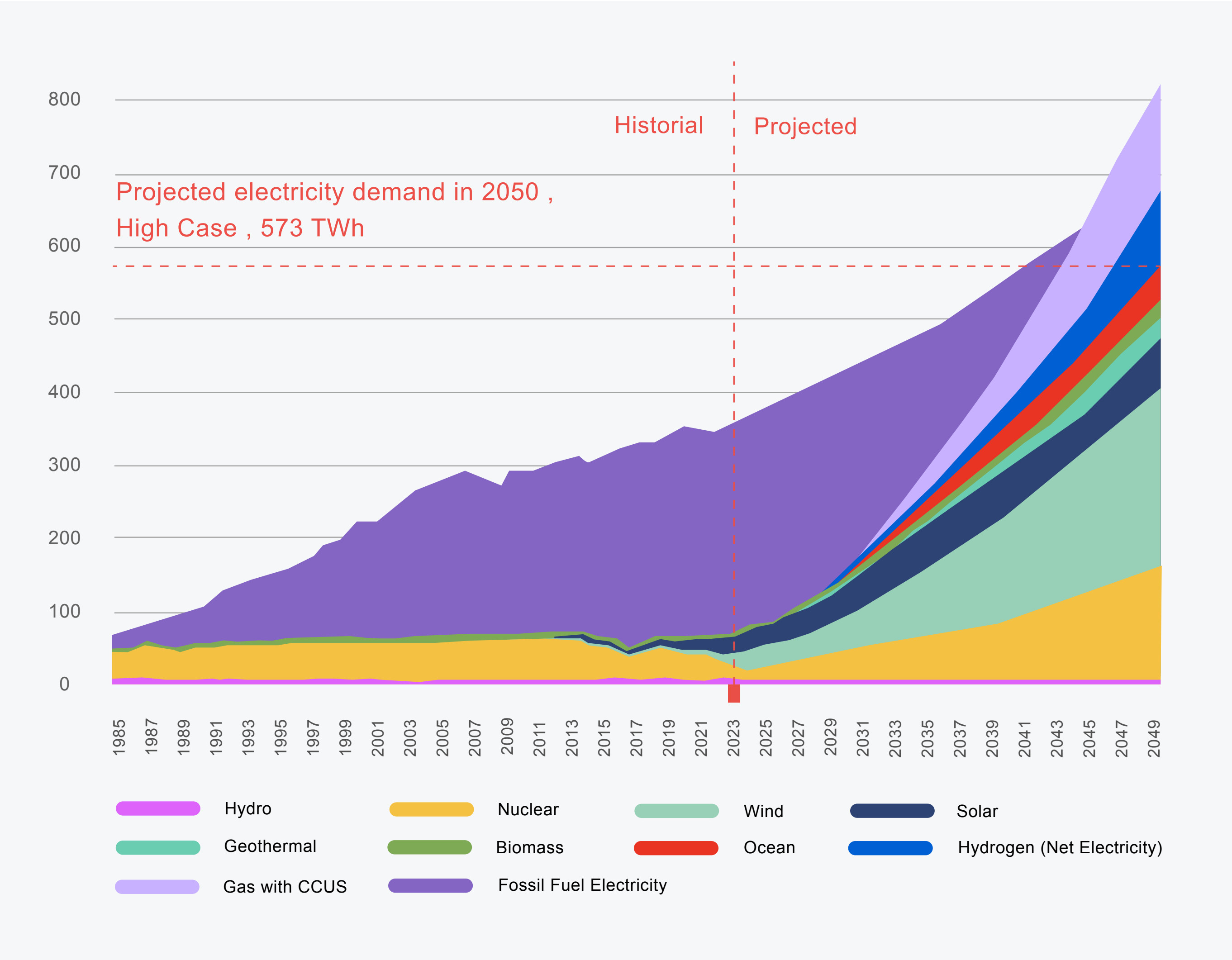
High Case Plus a Progressive Nuclear Program

The High case plus progressive nuclear program looks at what would happen if nuclear was not just added to the toolbox but done so with an expansive mindset. In this scenario, Taiwan would restart its existing nuclear fleet, similar to the projection in the Low case + nuclear program scenario presented earlier. It would add 5 TWh of new production per year between 2027 and 2037, on top of the current 10 TWh/year. In addition, this scenario assumes a Phase II, a doubling of the nuclear capacity between 2038-2050, by building ~8 GW of new capacity at the current sites (~2 GW for each).

The extensive program of refurbishing and uprating the current fleet and finishing the construction at Lungmen 1 and 2 would give the Taiwanese nuclear industry valuable experience and time to prepare for Phase II: the construction of new reactors at the current sites. Given the long lead-in times of nuclear projects, action on the new-build project would likely start in mid 2020s, and construction of the first new units would start around 2030, with subsequent construction projects starting every 12-24 months from then on.

Taiwan's Historical and Projected Clean Energy Generation Net - Zero Roadmap - High Case + Nuclear Program



As seen in Figure XZ, the first unit would come online around 2038 with a further 5TWh added each year, continuing the 5TWh per year addition we had with the restarts of the current fleet. By 2050, Taiwan would produce around 130 TWh of nuclear electricity, around 18% of total electricity production of 735 TWh, or 23% of the projected High case demand of 575 TWh.

To minimize technology and operational risks, it would make sense to deploy proven water-cooled reactors, which the Taiwanese industry already has extensive experience operating. Because the main objective is to produce electricity for the grid at a large scale and with reasonable load-following capabilities, it would likely make sense to build currently available large or mid-sized reactors.

Discussion on High Case + Nuclear Program Scenario

As demonstrated, this scenario would add significantly more clean electricity by 2050 than needed to meet the projected demand. There are multiple ways to look at the benefits this would bring, but the main theme would be de-risking, as the nuclear capacity would act as a safety valve, greatly decreasing the pressure on everything else to succeed.

First,

it would de-risk the demand growth projection. What if the demand from Taiwanese industry and other consumers grows faster than projected – perhaps due to growth in the semiconductor industry or a faster-than-expected proliferation of electric vehicles and air conditioning – or if new industries or clean hydrogen demand emerges, without opportunities to import at scale.

Second,

it would de-risk the deployment of other technologies. Many of the projections are, by necessity, mainly just educated guesses. Offshore wind deployment can be seen as especially risky, given that it is already an expensive way to deploy clean electricity production, but if projects need to move from seabed installation to floating platforms, the cost will rise even higher. The ability of ocean energy and geothermal to scale up is also still somewhat unknown. Solar would also require significant areas of land, something that is not abundant in Taiwan and is already used for other purposes.

Third,

having an energy source with great security of supply would significantly de-risk LNG imports, both from a terminal construction and availability point of view, but also from a global market risk perspective. It would also mitigate other supply disruptions, for example, hostile acts. Modern nuclear plants have great load-following capabilities, making them suitable for playing a similar role in the electricity system as a fleet of combined cycle and open cycle gas turbines. If less natural gas with CCUS were needed, there would also be less need for CO_2 storage facilities, which would decrease costs.

Fourth,

the larger nuclear fleet would de-risk imported hydrogen that is needed to handle the extreme volatility that high shares of wind and solar bring to the daily supply. Hydrogen would need to be imported, meaning a global supply risk. It would also need to be stored in large quantities to manage the supply risk, but also to prepare for longer periods of lower wind and solar supply. Extra electricity production can be used to manufacture hydrogen domestically, increasing security of supply significantly and lowering the need to store large quantities. Even if hydrogen was made mainly when there is oversupply of electricity, the number of those hours per year would greatly increase if there was around 15 GW of nuclear available at all times in addition to everything else. Having 16 reactors with a total capacity of roughly 16 GW would mean that on average, one of the reactors would be down for annual refueling and maintenance at any given time.

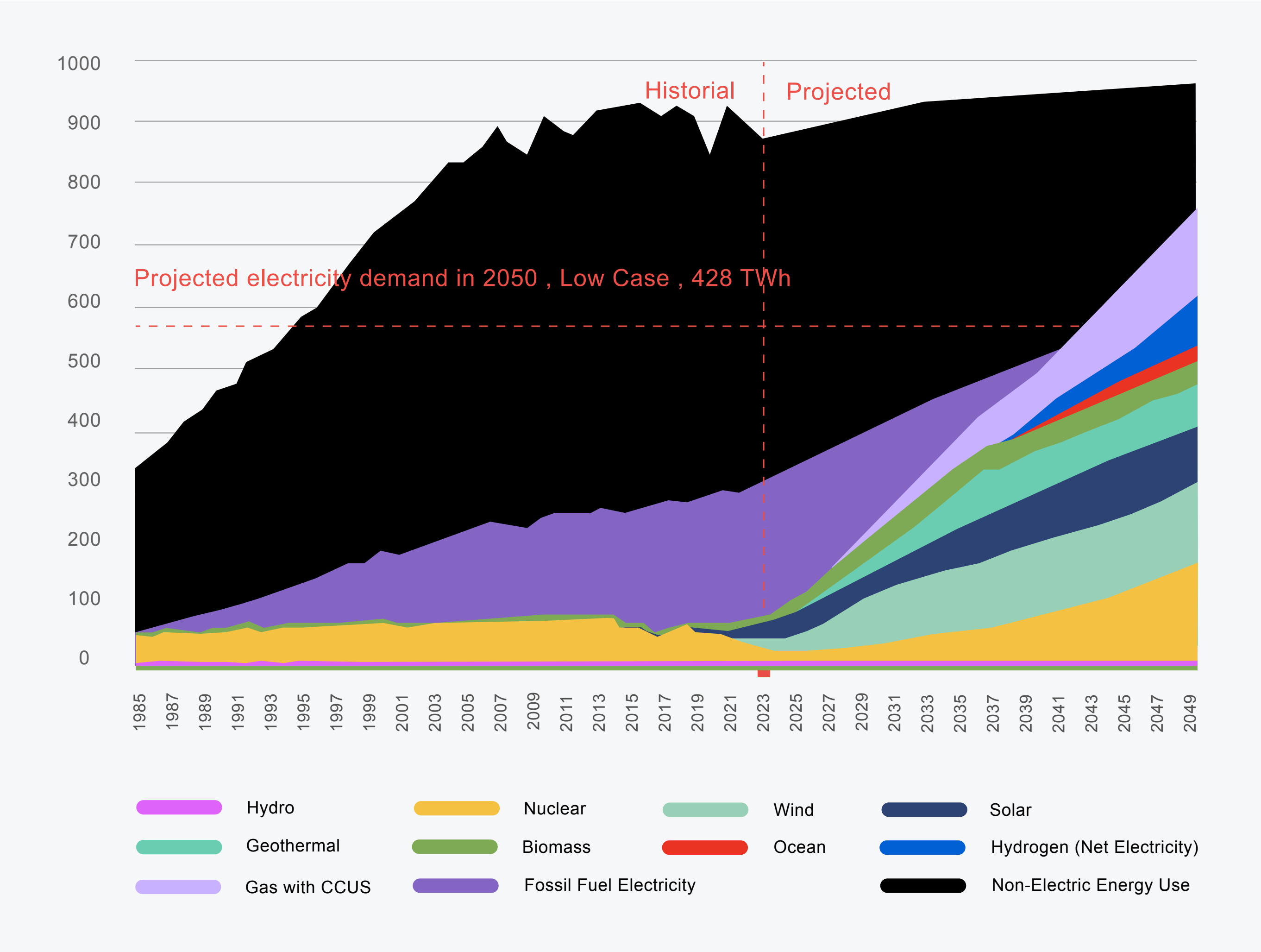
Fifth,

15 GW of stable electricity production would de-risk grid stability issues and make the duck curve easier to handle. It would also decrease the costs and LNG/hydrogen storage capacity needed to prepare for longer periods of low solar and/or wind output.

Finally,

it would de-risk the projected carbon sinks that are needed to manage the emissions from non-electric energy use, see Figure ZX. As there would be extra supply of clean electricity (143 TWh in 2050), it could be used to either further electrify society or to make hydrogen, synthetic fuels, or other chemicals that are now made from fossil fuels. This would decrease the non-electric energy use emissions, reducing the demand for growing carbon sinks.

Taiwan - Shared of Energy Sources in Electricity Generation Net - Zero Roadmap - Low Case



Almost 78% of final energy use would be for electricity in 2050. It is questionable whether this much of the economy can be directly electrified by 2050. This is due to fuels having many useful properties electricity does not. Most of the remaining fossil fuel use can be electrified indirectly through the manufacturing of synthetic fuels and chemicals with clean electricity. While direct electrification often improves efficiency (electric motors are more efficient than internal combustion engines, heat pumps are more efficient than boilers for space heating, etc.), indirect electrification can decrease it. This is discussed in more detail in the final scenario.

Summary of High Case + Nuclear Program Scenario

Having the nuclear fleet acting as the backbone of the power system would bring a lot of much-needed breathing room and flexibility into the Roadmap. Extra production of clean electricity would greatly ease the pressure for everything else to go just as planned to hit the net-zero targets while maintaining reliable grid and high-enough security of supply.

Grid stability would also be much easier to manage, both through daily variations (the duck curve) and through longer lulls in solar and wind production, as there would be a reliable base of production. The nuclear fleet would provide the grid with valuable spinning reserves which increases reliability as well. Security of supply would also be greatly enhanced, as nuclear fuels are relatively low cost and very easy to store compared to fossil fuels or other energy carriers such as hydrogen or ammonia.

The Taiwanese nuclear program could perhaps be best viewed as an insurance policy or de-risking instrument. Without nuclear, everything else is harder and needs to get much closer to perfection than with it. As the years go by, a clearer picture will slowly emerge of the overall progress. If everything is going well, the nuclear program can be pushed with less urgency or scaled down. It is also an open question whether the lifetime of the current fleet can economically be extended far beyond 2050. It is quite likely that this fleet would need either major refurbishment or replacement between 2040 and 2070, depending on the reactor. Planning for these types of long-term maintenance programs needs to be done years or decades in advance, and they, therefore, require a stable political environment.

If Taiwan shuts down its nuclear sector now, as is the plan, it cannot be quickly restarted, even if the country later realizes that nuclear power is direly needed. Restarting and rebuilding the nuclear sector and supply chains from scratch is, as we have learned from the examples in Europe and the United States, slow, painful, and very expensive. Keeping the Taiwanese nuclear industry developing and gaining experience might also lead to export opportunities in the field. There are dozens of countries discussing or planning their first nuclear reactors, so nuclear is becoming more and more a growth sector.

Deep Decarbonization with Advanced Heat Sources

In the final scenario, we take a closer look at the remaining non-electric energy consumption and imported LNG and hydrogen, and how to decarbonize and produce them locally with advanced heat sources. Given that the large-scale deployment of these energy sources is likely still a decade or more in the future – assuming a deployment starting in 2040 – we stretch this scenario timeline to 2070.

The main goals of this scenario exercise are to bring the full scale of deep decarbonization into view, and to include the potential and promise of advanced heat sources in the discussion. While the deployment rates might appear large, up to 5 GW of thermal capacity (GWt) per year, it should be remembered that we already use energy at these scales, but the energy is mined or pumped from underground as fossil fuels. This scenario is purely for illustrative purposes.

The key assumptions include:

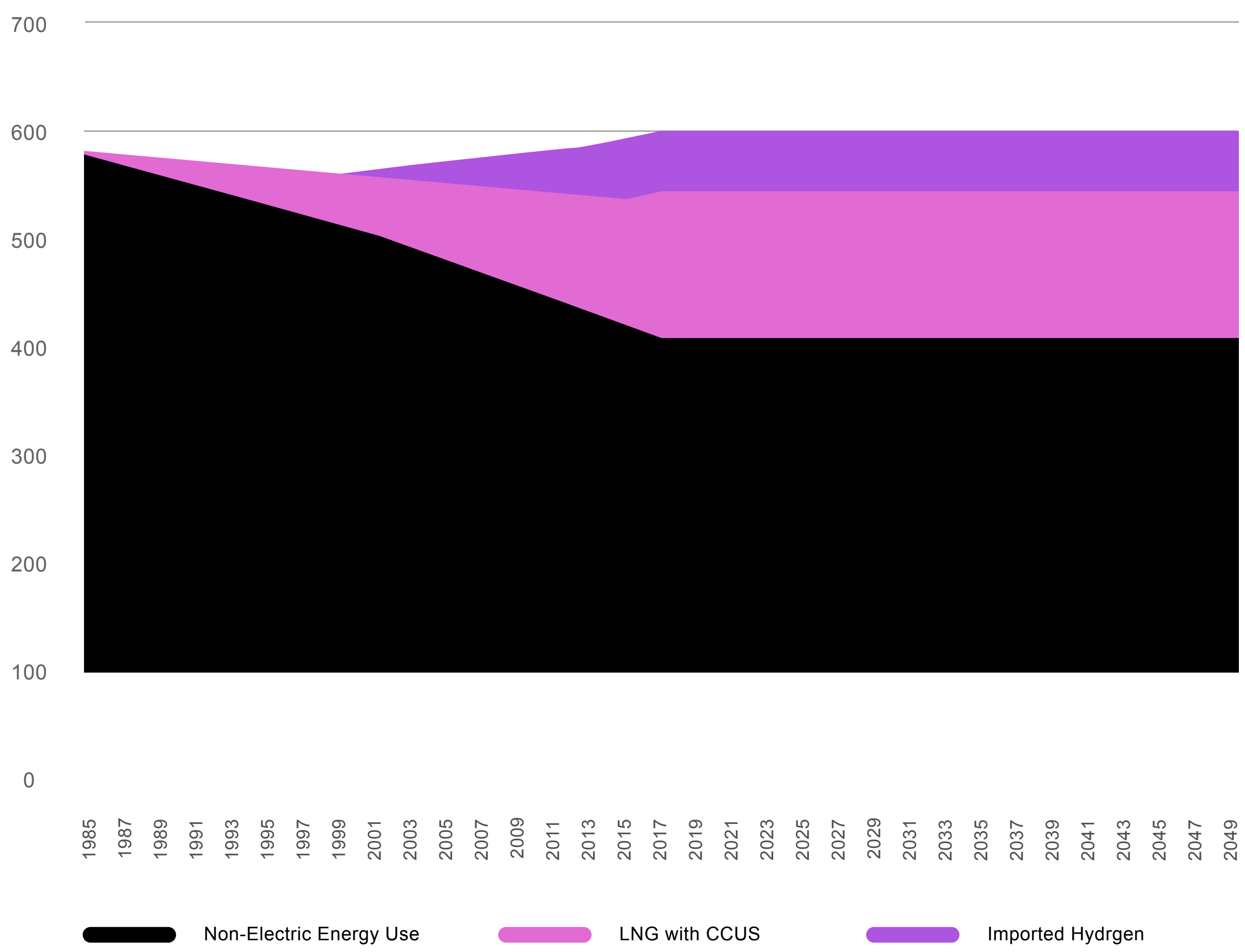
1. It focuses on non-electric energy, LNG with CCUS and hydrogen (for electricity), see Figure VC below.

2. The high case for clean energy deployment and demand growth is assumed until 2050.

3. From 2051 to 2070, non-electric energy use, LNG with CCUS and hydrogen (for electricity), are assumed to be stable, meaning that practical, direct electrification of the economy has reached its limit at 61% of final energy use.

4. Advanced heat sources are used only to replace the above-mentioned non-electric energy use and LNG with CCUS and hydrogen for electricity generation. The motivation is to replace direct fossil fuel use with clean fuels and reduce import dependence on LNG and hydrogen.

Taiwan's Historic and Projected Electricity Generation Net - Zero 2050 Roadmap , Low case



Advanced heat sources include next-generation factory- or shipyard-manufactured advanced nuclear reactors of various sizes and types as well as super-hot rock geothermal. The key common denominator here is that their primary product is reliable high-temperature (300-600°C) heat that can be used directly for industrial processes and for making hydrogen and synthetic fuel with the more efficient high-temperature steam electrolysis process and running those facilities at an 85% CF.

The four main use cases for thermal power are:

1. Industrial heat, which needs to be produced near the end-use as supercritical steam, is hard to transport long distances. This will help replace coal and LNG in industrial uses.

2. Flexible electricity production, with molten-salt thermal energy storage systems that allow the advanced heat source to run 24/7, but equipped with steam turbines that can produce electricity for the 8-16 highest value hours of the day. This will help replace imported hydrogen used in electricity generation as well as open-cycle gas turbines and grid batteries.

3. Hydrogen production, either through conventional electrolysis or, more likely, through the more efficient high-temperature steam electrolysis. The hydrogen will be used to replace imported hydrogen in electricity generation and in industries such as iron reduction and oil refining.

4. Synthetic fuels production. First, hydrogen is produced, which is then used as a feedstock to make clean ammonia, methane, methanol, jet fuel, and other chemicals.

For simplicity's sake, we assume that each of these use cases will require 25% of the available primary heat. The heat will be used with 100% efficiency (a simplification made purely for convenience). Electricity will be generated with 45% efficiency. Hydrogen will be made with 90% efficiency from electricity (using high-temperature steam electrolysis). Synthetic fuels will be made with 60% efficiency from hydrogen (a mixture of ammonia and hydrocarbons, including the energy needed to capture nitrogen or carbon).

Regarding advanced heat source deployment, we assume that deployment begins in 2040 with 500 megawatts of thermal power (MWt). In 2041, another 500 MWt is added, and then annual deployment starts to grow by an additional 500 MWt per year, until in 2050 5,000 MWt is added. After that, another 5,000 MWt is added each year, netting a total capacity of 128 GWt in 2070, see Figure ZX.

Capacity Deployment of Advanced Heat Sources

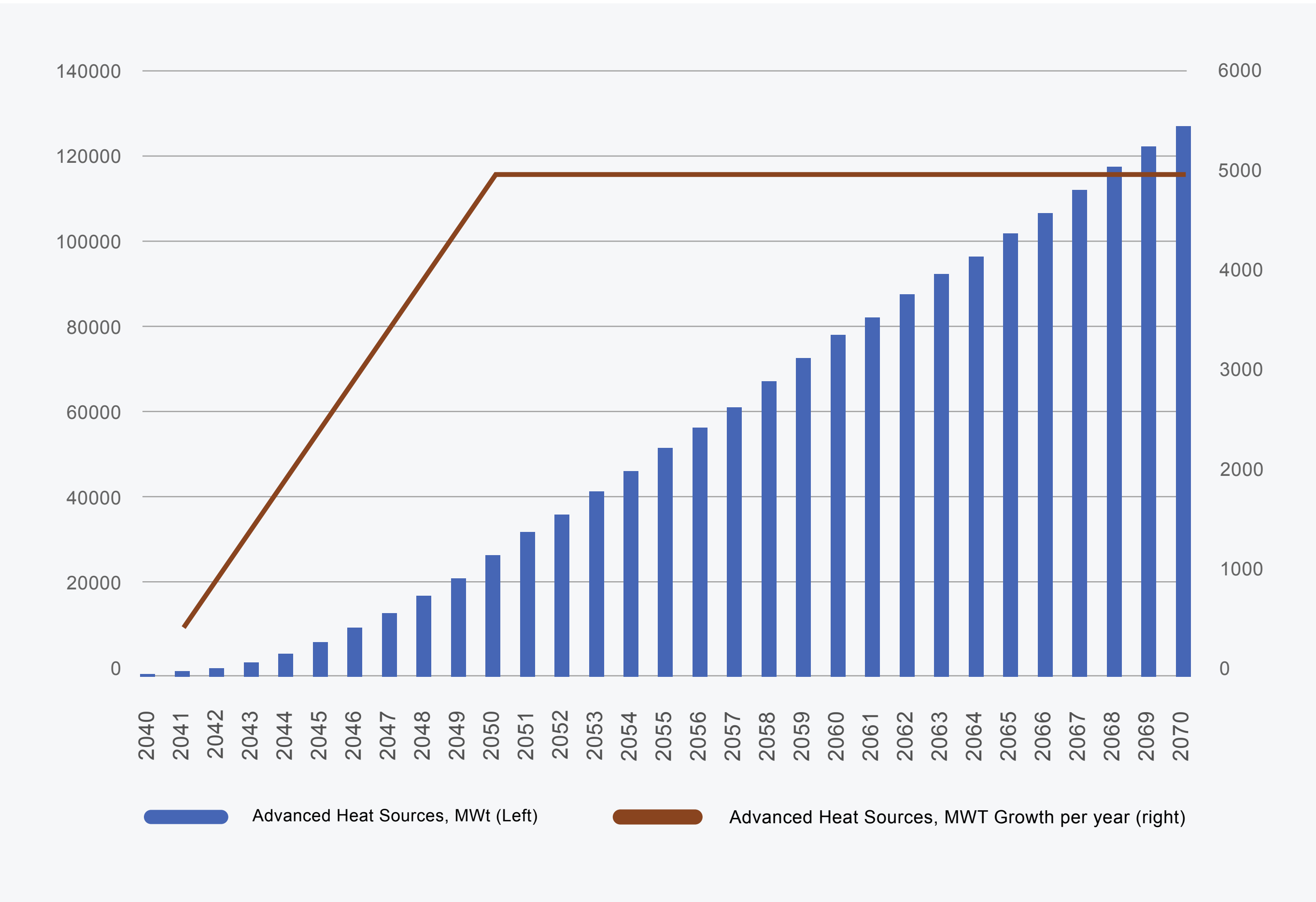
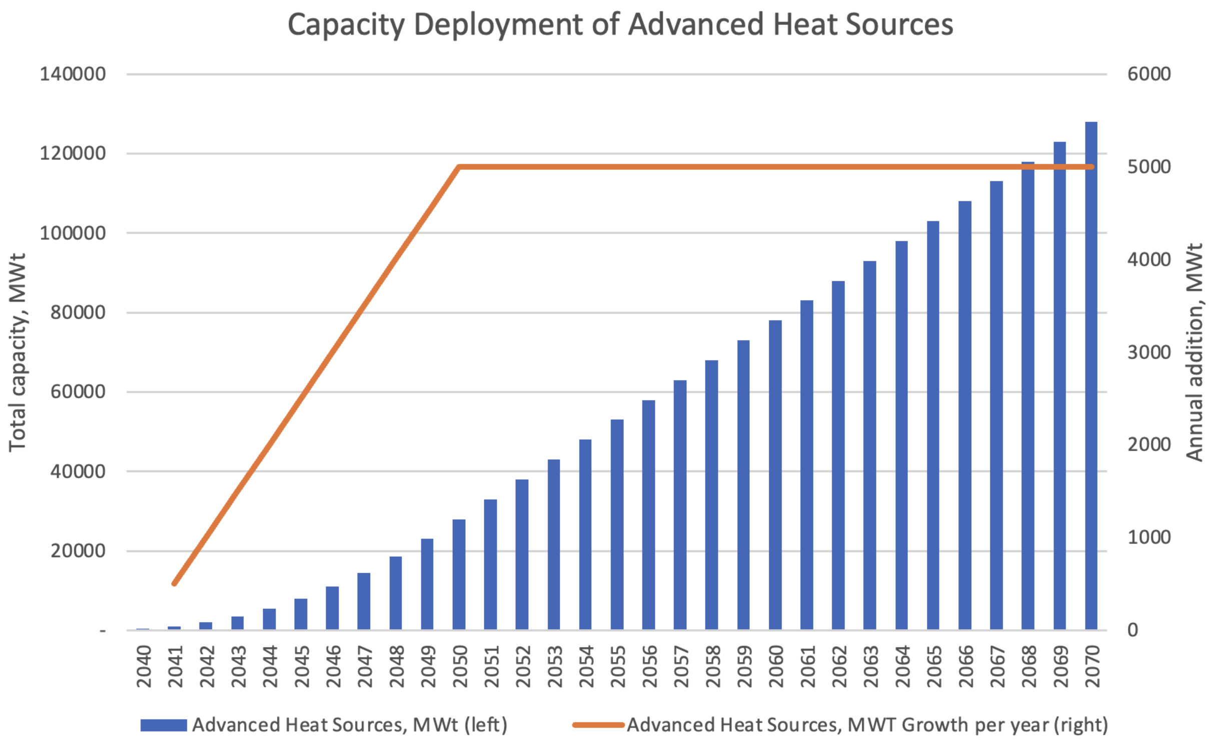


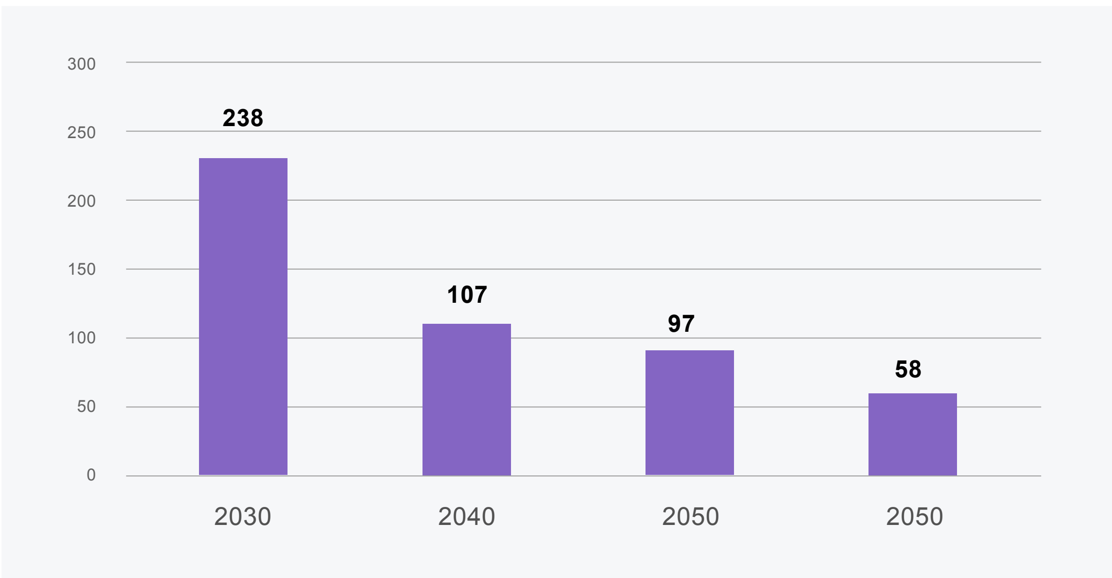
Figure CV shows how the primary heat is turned into four different products: industrial steam, flexible electricity, clean hydrogen, and synthetic fuels and chemicals. Each category uses 25% of the available heat, and the amount of product output depends on the conversion process efficiencies of heat -> electricity -> hydrogen -> synthetic fuel.

Advanced Heat Sources Deployment by Product Type



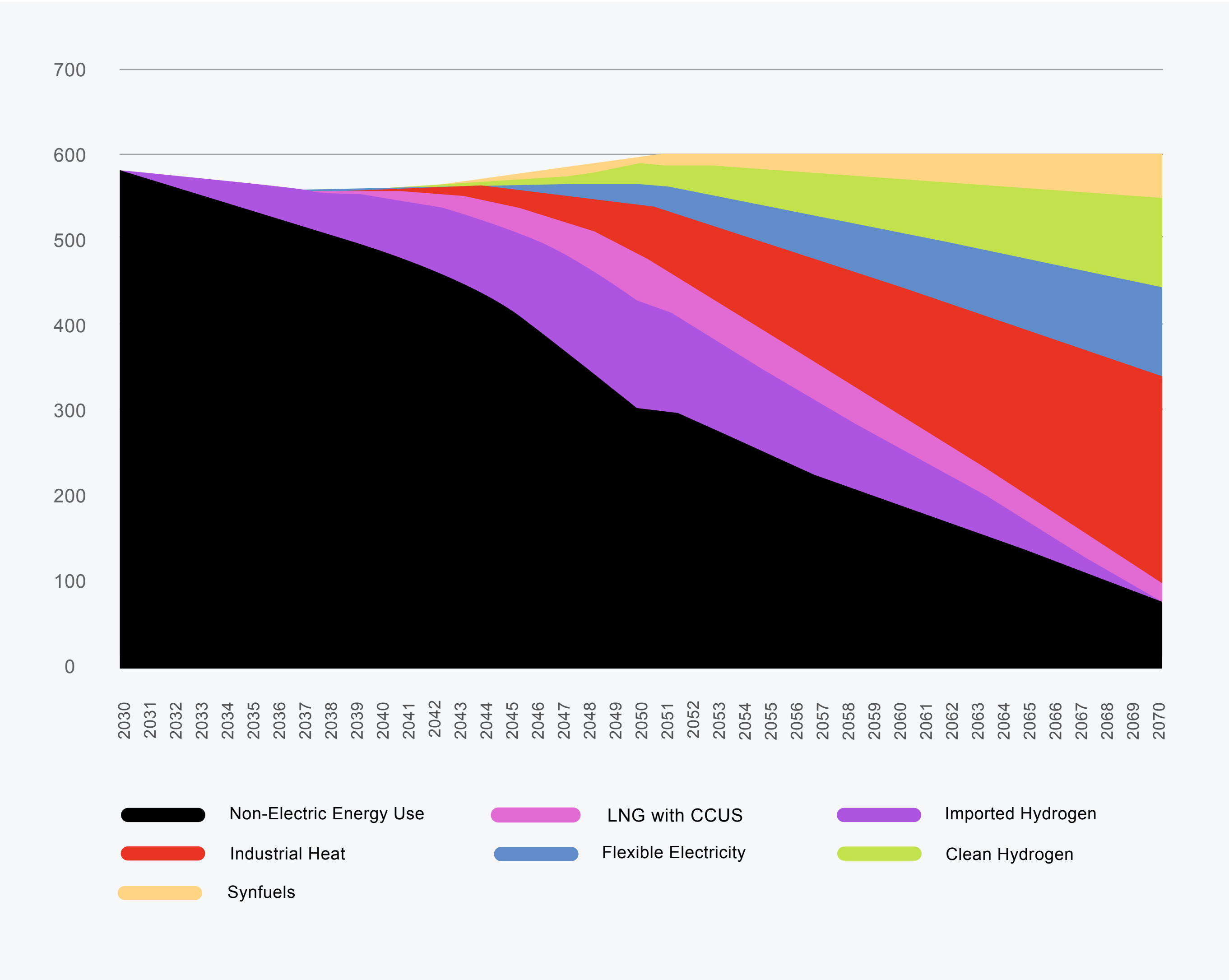
), operating at an average 85% CF would produce a total of 953 TWh of high-grade heat. These are made into 500 TWh of various energy products.

Energy Product Output from Advanced Heat Sources by Type



Finally, Figure SD shows how these energy carriers and services could replace non-electric energy use, imported LNG, and imported hydrogen. In the graph, 60% of the total output is used to replace non-electric energy use, 30% is used to replace imported LNG, and 10% is used to replace imported hydrogen. These choices are arbitrary and just for illustrative purposes to clarify the scale needed for deep decarbonization. In 2070, only 100 TWh of imported chemical fuels remain.

Advanced Heat Sources Replacing Fossil Fuels in Energy Mix



This scenario is a simplification and ignores everything else happening in the electricity system. For example, by 2070, the offshore wind farms will have to be built and then rebuilt at least once, some twice, and the same goes for the solar PV farms. Geothermal capacity will also need to be redrilled at least once. Between 2040 and 2070, six of the oldest nuclear reactors might reach retirement age as well and need to be replaced or at least heavily refurbished to extend their operations beyond 80 years. The advanced heat sources, regardless of which technology is used, will also have operational lifetimes and will need maintenance, refurbishment, and eventual replacement.

Summary of Decarbonizing Fuels with Advanced Heat Sources

Taiwan, and humanity in general, uses fossil fuels at an immense scale. Replacing them with clean electricity, heat, and synthetic alternatives will require investments and deployment at similarly large scales. Globally, roughly half of all energy is used as heat, either for space heating, warm water, or in industrial processes. Over 90% of this heat is produced with combustion of chemical fuels. Another quarter of our energy is used as transportation fuels, and just 20% as electricity.

Much of these uses will be replaced with direct electrification, but certain sectors will remain dependent on liquid fuels, such as long-distance aviation, marine shipping, and some heavy machinery. Making these fuels with heat and electricity will require much more energy input than we get out of the fuels. Depending on the electrolyzers, processes used, and the chemicals made, the overall efficiency of synthetic fuels production from electricity to fuel is roughly 50%. The input energy needs to be as low cost as possible, the electrolyzers need to be efficient and low cost, and they need to run at high CFs to make competitive clean fuels.

Even with a 61% electrification rate by 2050 in the High case scenario, a significant amount of non-electric energy use remains while a significant portion of the electricity is produced with imported fuels – LNG and hydrogen. The advanced heat sources scenario illustrates the order of magnitude of capacity that is needed to deeply decarbonize our energy supply beyond just electricity. The good news is that with this type of mass deployment, costs are likely to come down rapidly.