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Kuroshio power plant development plan

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ABSTRACT

As a country lacking energy reserves, Taiwan imports 99.2% of its energy, with only a small portion of indigenous energy, such as hydro, wind, and solar. In 2008, each Taiwanese spent 85,000 NTD dollars (1 USD $\sim$ 32 NTD) to purchase oil, coal, gas, and nuclear fuel from foreign countries, accounting for a total payment of 1.8 trillion NTD, more than the annual budget of the Taiwan government of 1.7 trillion NTD. In the same year, Taiwan emitted about 1% of the world's greenhouse gas (GHG), or 12 tons per person-year, ranking 18th globally. These situations in terms of energy security and carbon emission are very severe.

To resolve these severe situations, harnessing the power of the Kuroshio in eastern Taiwan offers a great opportunity. The Kuroshio is a branch of the North Pacific Ocean current. Due to the westward-enhanced effect, this ocean current is strong and stable as it passes through eastern Taiwan. The flow rate is about 30 sverdrup (Sv) or 1000 times that of the Yangtze River, the average speed is 1 m/s, the flow direction is fixed to the north, and the flow path is close to the east coast of Taiwan. By precisely locating high-quality sites and implementing sequential works with careful planning, one can possibly generate exploitable power more than 30 GW. With 30 GW of clean energy, Taiwan could effectively enhance energy security, reduce GHG emission, and lower energy-purchasing cost.

This paper proposes a feasibility study to explore the power of the Kuroshio. The content consists of four parts: (1) assessment of Kuroshio power reserves, (2) development of turbine generators, (3) development of turbine-anchor system, and (4) deep-sea marine engineering of turbine clusters. By integrating these technologies above, we propose a project to construct a 30 MW pilot plant. In this project, we also discuss the financial analysis and propose new regulations, environmental impact analysis, risk assessment, and other relevant issues.

Contents

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1. The flow characteristics and energy reserves of the Kuroshio in eastern Taiwan

The Kuroshio current, with a width of about 100 km and a length of about 400 km, flows along the eastern coast of Taiwan toward the north [1], as shown in Fig. 1. The Kuroshio current mainly comes from the south, while a significant portion injects from the east. These two waters provide the momentum required to push the Kuroshio current northward to Japan under the effects of various types of frictions (e.g., frictions with land, seabed, atmospheric circulation, and turbulence).

The velocity of Kuroshio changes, due not only to seabed and coastal terrain variation (ex. it accelerates when passing through the channel between Taitung and the Green Island), but also to seasonal monsoons. For example, a northeast monsoon in winter can significantly slow down the Kuroshio. Short-term factors also affect the flow, such as invasive typhoons, temperature gradients, seawater salinity, and varying sea levels due to atmospheric pressure gradients [2–9].

Similar to the Florida Gulf Stream, the Taiwan Kuroshio is also known as the Western Intensified Flow [11]; the farther west it travels, the stronger the flow becomes. Atmospheric circulation in the North Pacific (or Atlantic) is typically regarded as the driving force behind this intensified flow. At 30–45° north latitude, the wind due to the atmospheric circulation is moving from west to east, but changing its direction at 15–30°. This circulation leads the ocean current to rotate clockwise in the North Pacific (or Atlantic).

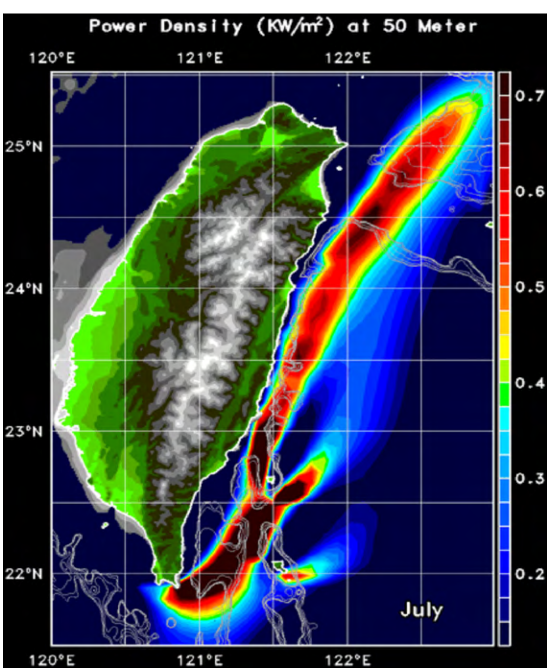

Fig. 1. Average velocity profile of ocean current at the average water depth of 50 m, resulting from the computation by Chao [10] by combining the global ocean computation program with timely satellite data from the sea surface in 2007. When Kuroshio flows from the Philippines in the south into the eastern waters of Taiwan, the current is very strong and then amends from seabed changes among Orchid Island, Green Island, and Taiwan, and finally flows along the east coast of Taiwan toward Okinawa.

The current extrudes westerly and gradually strengthens the energy intensity, resulting in the Kuroshio or the Western Intensified Flow. The two ocean circulations in the Northern Hemisphere are known as the Geotropic Current [12], which is resulted from the force balance among the flow momentum, the Coriolis force and the hydrostatic force due to sea level difference. To balance the Coriolis and hydrostatic forces, the momentum of the Kuroshio flow must be strong and stable. On the other hand, subjected to these two forces, the Kuroshio flow can also accelerate as it flows northward. As a result, intermittently the increased flow rate could exceed three times the normal rate [13].

Both ocean flow simulation [14] and on-site single point measurement [15,16] indicate that the flow rate of the Taiwan Kuroshio is generally around 20–30 $\times$ 10^6 m^3/s (or 20–30 sverdrup, Sv), which is about a hundred times greater than Brazilian Amazon River and a thousand times greater than the Yangtze River or the Mississippi River. By calculating the total energy with the flow velocity over 1 m/s, this study finds that the power approaches to 5.5 GW for several representative cross sections [10]. According to Fig. 2, monsoons and seasonal variation influence the total power that can decrease to 4 GW in winter and increase to 10 GW in summer. Although the exploitable energy potential is huge, the development of the Kuroshio power plant can be limited. The environment and ecology concerns and how much energy to capture without significantly impacting the circulation of the North Pacific Gyre are essential issues to be resolved. A detailed computer simulation and long-term monitoring from fixed instruments can answer these questions. The assessment is generally based on the following natural or man-made factors: (1) types of turbines; (2) density of turbine deployment; (3) flow characteristics in the sea of power plant; (4) seabed topography and geological features in the sea of power plant; and (5) other aspects, such as environmental

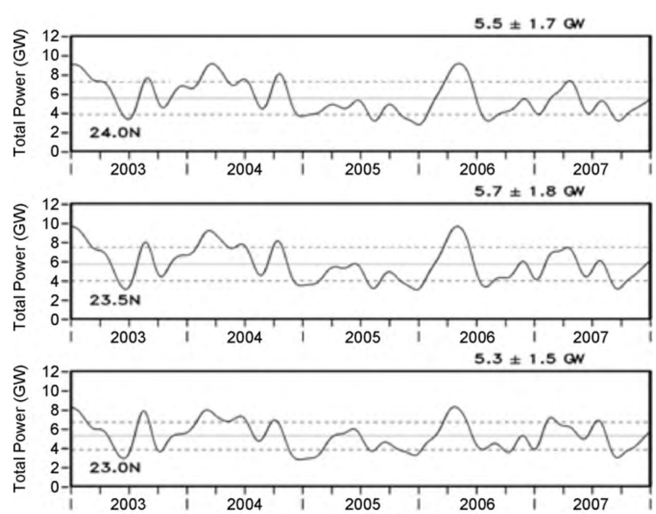

Fig. 2. Kuroshio energy changes with time in three cross sections. The locations of these three sections are respectively at north latitudes of 23° (near Green Island in Taitung), 23.5° (near Hualien), and 24° (near Su-ao). This figure reveals the following phenomena: (1) energy changes in three sections are almost synchronous; (2) the more north the more energy; (3) energy at each cross section can be up to 10 GW maximally and reduces to 4 GW minimally (source: Chao [10]).

protection, fishing rights, national defense, international intervention, among others. After a preliminary assessment, we believe that developing a Kuroshio power plant of 30 GW is feasible if the planning is done sufficiently precisely.

2. What is the Kuroshio power plant?

After a number of discussions with experts in various fields, we construct a schematic draft of the Kuroshio power plant, as shown in Fig. 3. In this figure, there are three clusters of turbine generators, each is individually anchored on a floating platform that can deform with ocean flows and fixedly anchored to the seabed. The floating platform is made of hundreds of hollow floats connected by ball-joints, can accommodate 20–30 turbines. The total area of the extent is 100 m $\times$ 500 m. To avoid serious impact caused by big waves due to typhoon, the turbines should be laid under the sea surface 30 m or deeper, while the platform can be laid about 100 m under sea level. Although the axes of the turbines in Fig. 3 are designed to parallel to the flow, the turbines with vertical axis may be more appropriate for practical applications of Kuroshio power plant, please see the discussion of Section 3.1.

The floating platform is anchored to the seabed at a depth of 500 m or more by tens or hundreds of cables, and the position of each cable anchored to the seabed can be undetermined in advance. However, the cable extension must be complied with the flow motion to eliminate possible large displacement or deformation when the entire floating platform is exposed to strong current. This "random anchor" approach avoids possible looseness of the anchor due to seabed displacement caused by frequent earthquakes in eastern Taiwan, thus decreasing the risk of collapse of the entire structure. Moreover, this approach substantially reduces the cost of overall construction since the anchor position can be chosen randomly. However, the anchoring position of the turbines on the platform cannot be arbitrary because the anchor points are responsible to platform structure robustness. When dozens of turbines are functioning simultaneously in the ocean currents, the overall robustness of the platform has to be within safety tolerance to sustain excessive stresses. Therefore, the design process must consider whether the dynamic response behavior of the overall system will cause fatigue or destruction in the structure.

In each floating platform, we install a set of power conversion equipment. After modulating the electricity frequency, the power generated by the turbines in each group transmits to the terrestrial network system via power cables. To avoid damage caused by earthquake, the cables should hang on the platform without touching the seabed, then link to another platform, and finally connect to land. This method does not need to deploy undersea cables, and thus not only reduces cable length, but also avoids snapping cables due to the seabed slip caused by earthquake. The distances between platforms depend on the flow conditions and turbine performance, and can be shortened if put on different depth levels. Preliminary assessment about construction feasibility, maintenance convenience, and cost effectiveness reveal that a group of 25–30 turbines anchored on a platform of 100 m $\times$ 500 m is an optimal combination. Turbine movement under this kind of assembly can most coordinate with the floating platform, enabling effective control of its interaction with the flow motion within a safe range. In addition, the distance between each platform also depends on fish activity. Estimation is generally based upon the benchmark that the setup does not influence fish activity and ecological succession.

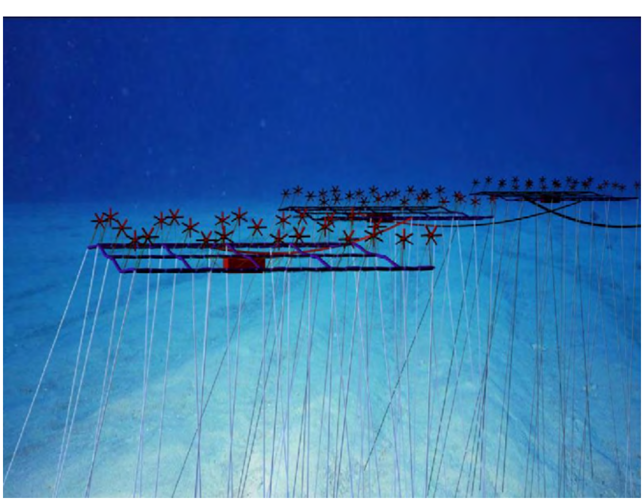

Fig. 3. Schematic illustration of the Kuroshio power plant. This figure shows three groups of turbine generators (or three turbine clusters). Each cluster has 25 turbines and a transformer fixed on the floating platform. Electric cables connected among clusters transmit the electric power. The floating platforms are anchored to the seabed by tens of cables.

3. Construction of Kuroshio power plant

Most techniques related to the construction of the Kuroshio power plant are fully developed, but it is a new attempt to integrate these technologies into this kind of marine engineering. Although there have been many tidal power plants in the world, they are nevertheless designed for shallow-water sea area. The ocean depth in eastern Taiwan is mostly more than 500 m, and many areas are even deeper than 3000 m. Although deep-sea marine engineering is not a new technology (ex. offshore oil-rigs and drilling techniques in the Gulf of Mexico are done on a seabed of about 3000 m deep), to construct Kuroshio power plant in eastern Taiwan is intrinsically different from existing one because to anchor hundreds of turbines securely on the deep seabed with frequent earthquakes is definitely a tough challenge in various aspects.

The following subsections divide the techniques into three categories, according to their engineering characteristics: turbine generator design, anchor system design, and plant engineering design. With the existing information, the following further describes and discusses these designs.

3.1. Turbine generator design

An underwater turbine generator is a device that converts kinetic sea flow energy into electricity. Its basic principle is simple, with little variety. The mechanical structure comprises three main components. (1) The turbines: converting linear momentum of the ocean current into rotary kinetic energy. (2) The generators: converting rotary kinetic energy into electrical energy. (3) The gear set: an interface between turbine and generator, capable of adjusting rotating speed and absorbing axial impact force. Other ancillary equipments include electronic power conversion equipments, submarine cables, devices to link cables, and so on.

A variety of marine turbines is available in the market, but most are designed for tidal power plants in shallow seas, mostly developed in Europe and the United States. According to the principle of action, these turbines consist of four categories: horizontal axis, vertical axis, reciprocating type, and others. Sixteen manufacturers worldwide have made prototypes tested on the sea, and another 12 companies have made scale-down models tested in the laboratory tank. Twenty-five manufacturers have claimed different designs, but without any entity or model testing. Appendix A lists the companies that have tested their designs. In addition, we also list the representative types of machines, together with their performance in Appendix B, in which

the vertical axis turbine has two types: standing and lying. After preliminary analysis, the turbines with vertical axis may be the most suitable for the Kuroshio power plant. This is because in deep-sea engineering, its construction and maintenance cost is lowest and stability is highest. Therefore, in Appendix C, we briefly introduce the characteristics of this kind of turbine according to the information collected by Shyu [17].

A preliminary survey obtains some key techniques for manufacturing turbine generators. The following discusses the details.

1. Design and analysis of turbine power: Turbine performance depends on the flow pattern of the machine body and blades. Several factors affect the pattern, such as the average and characteristic speed of water flow, short wave, long wave, typhoon, or other special environmental effects. Body design should consider several parameters, for example, the shape and structure of the shell, and the size, profile, number, attack angle of blades, etc. [18–22]. The design also needs to account for maintenance procedures and methods, as well as typhoon effect on the turbines. Academic researches and practical engineering applications have already developed the analysis method of fluid dynamics for such a design.
2. Composite materials: The main structure of the turbine machine is not complicated, composed of a rotary machine with three to five blades. To increase energy conversion efficiency, this study wraps a well-designed shell around the machine. Except for the trunk parts, such as the bearing and frame, made by particular alloys, other components can be made of composite materials. Producing composite materials requires mold design and a manufacturing process, with some specialists and skilled workers to design the production lines and supervise the procedures. The associated techniques are available, given Taiwan's long establishment of many technical energies and experiences that are now beyond international standards.
3. Generator: The characteristics of marine turbine generators are low speed, high torque, small radius, and long shaft. In Taiwan, there are many manufactures capable of designing, manufacturing, and assembling small and medium capacity generators; however, large Western and Japanese electrical and mechanical firms still hold core technologies. Such technologies are mature, and the current domestic cost is about 6 million NTD dollars/MW. A large enough purchasing amount should further reduce cost.
4. Gear set: Sea turbines must withstand high torque under low rotational speed and high axial thrust. The gear set absorbs both the static forces and the dynamic response, and then transferred into torques for the generator. The related techniques include gear-change, mechanical and dynamical analysis, corrosion and water-repellent techniques, etc. The design phase needs to consider other related issues such as maintenance, lubrication, cooling, etc. The wind turbine industry has developed the design and manufacturing of the gear-switching set. Most machinery manufacturers in Taiwan possess mature techniques, and many of them are capable of exporting their products. Therefore, applying these techniques to sea turbines should not be difficult.
5. Corrosion warranty: Because deep-sea turbines will be placed hundreds of meters deep all year round, the possibility for oxidation corrosion is less than with shallow-water turbines. However, biological attachment in the deep sea is likely to occur. Previous bio-adhesion coatings for preventing biological attachment have inevitable toxicity, and most are prohibited by environmental protection laws. Therefore, finding a suitable pharmaceutical chemical synthesis may be necessary for developing a new non-toxic paint. In addition, some metal components require processing by either plating or lubrication to avoid rapid corrosion. These anti-corrosion processes must account for maintenance periods and procedures.
6. Maintenance: All maintenance and repair works are associated with operating costs, and the maintenance procedures of the sea turbine have an absolute relationship with the design of the machine itself. Hence, maintenance procedures and repaired items should be set up clearly at the beginning. This includes the procedures, frequency, and maintenance period, and the replacement of parts and lubricants. For example, shutdown frequency is one time per year in principle, and the turbine machines must rise to the sea surface during annual maintenance. Several manufacturers (some listed in Appendix I) have claimed the capability of creating turbines without maintenance in the first 5 years after starting use.
7. Depreciation: If the design goal for the turbine machine lifetime is 25 years with full loading for 10 months, the procurement specifications should be achievable.

3.2. Anchor system design

Turbine-anchoring engineering involves three major issues: anchor mechanism, anchor material, floating platform. The key technologies include unit anchor design, turbine group sets anchoring, the floating platform design, dynamical analysis, and anchoring system design of the floating platform. In addition, the issues for corrosion, warranty, maintenance, and the depreciation estimate are also essential to anchor engineering design. The following elucidates the details.

1. Anchor mechanism: many forms of current anchors can be chosen [23,24], such as the caisson and piling type. The selection criterion is related to the local seabed geology. Based on seabed information near Taitung, sediment thickness may be several meters or more, analysis of the caisson weight and shape requires careful calculation. In the case of anchor piles, initiating construction requires detailed geological data under the sedimentary layer.
2. Anchor material: the traditional anchor is mainly made of steel, which may not be suitable for anchoring turbine because of its heavy weight and easy corrosion. A recent new anchor is made of composite material or polymers. These new productions possess advantages in weight, strength, and toughness. Some have a hairy tail at downstream capable of reducing the low-frequency swing or the high-frequency vibration due to flow interaction [25,26]. Such a material may be the best choice for the anchor system design in developing ocean power plants. This is especially true for the present case because the sea depth near Taitung is often more than 500 m, and the required anchor chain length may be over a thousand meter. To achieve this demand, the anchor must be light, but with strong intensity.
3. Floating platform: deploying a gigantic turbine of twenty meters in diameter on a fixed specific position undersea 50–100 m, and anchoring it on a seabed of more than 500 m deep, could be a formidable challenge. Moreover, there are sometimes hundreds of turbines gathered in several square kilometers of ocean area. The relative distances between the turbines must be relatively invariable, and too much uncertainty is unallowable. Therefore, deploying a mobile scaffold under the sea 100 or 150 m to form a floating matrix platform to anchor the turbines can effectively decrease the required length of anchor chain and significantly reduce the position fixation difficulty. On the other hand, the platform position is not necessarily very accurate if the relative distance between the turbines is firmly fixed. The required design parameters of components, such as the kinds and numbers of anchors and the extension angles of the chains, will become flexible. In a word, installing a floating platform between the

turbines and the seabed would increase relative position accuracy between turbines and significantly reduce anchor construction difficulty. The anchor platform can comprise hollow scaffolds, while the techniques related to scaffolds, such as the selection of material, mechanical analysis of structural stresses, fabrication and manufacturing procedures, etc., are all well developed [27–30]. The available scaffold materials vary widely, such as composite materials and polymers. We suggest assembling the platform on land before deploying undersea.

4. Anchor system: the whole anchor system combines the above-mentioned components: anchor, anchor chain, and platform. The interaction between the three components will induce inevitable relative motion, and the whole structure will vibrate when subjected to the strong impact of the ocean current [31–33]. The motion and vibration will affect the safety and lifetime of the whole turbine-anchor-platform system, and may decrease power plant efficiency as well. The mechanical analyses, such as the structural design of the anchor system, the static balance calculation, and the dynamic vibration analysis, are all key techniques of anchor engineering [34]. These works are mature techniques, making assembly less difficult.
5. Corrosion warranty: like turbines, all the anchor system components have bio-fouling problems, but the situations are not as serious as the turbine's since the anchoring system has fewer moving parts. Except for needing to monitor the degree of bio-fouling between the mobile parts of the anchoring platform, the other parts are mostly separate and monotonous. As long as the biological attachment does not cause severe corrosion, the anti-corrosion requirement of these parts would be not necessarily be too stringent.
6. Maintenance: the maintenance frequency is roughly once a year. The main work is to clear the bio-fouling and to check whether a abnormal structure exists between the parts. Repair and maintenance are all on sites, but for the deep-sea site that is very difficult. The anchor system design has to account for the maintenance procedure. A special submarine maintenance plan, with remote operation machines would be the best design. The key technologies would include how to eliminate dirt, clean biotechnology, and avoid damaging structures, and so on.
7. Depreciation: the design criterion is for a 50-year lifetime.

3.3. Power plant engineering design

The construction engineering of the Kuroshio power plant is divided into five parts: the turbines deploying engineering, the fixation engineering of the anchor platform, the strength design of the overall unit structure, the submarine cables and power-transmission engineering, and the land-based power plant engineering. For a Kuroshio power plant with installed capacity of 1 GW, there may be 500–1000 turbines deployed on the sea in an area of hundreds of square kilometers. The safe and efficient anchoring of turbines simultaneously is better done in groups of 30–50 turbines. A more effective method is to first design an appropriate floating platform for fixing the turbine group, and second to design a specific anchoring technique for deploying the platform. Other deploying methods include the whole construction process, the equipment dispatch, and the strength test of the unit structure, the transmission, and the distribution test of the partial and whole plant. These on-site methods are complex, and require complete planning. Since the construction engineering of a terrestrial plant is similar to that of general power plants, this design does not require any special consideration. Moreover, the constructors can design the special rig and equipment according to the site requirements and situations. Therefore, this paper does not discuss these two issues but discusses the first four main techniques described above for plant engineering.

1. Turbine deployment: To deploy hundreds or even thousands of turbines, with a diameter more than 20 m, on tens of square kilometers of sea area, the deploying procedure requires careful consideration. As mentioned earlier, dozens of turbines will be installed on the floating platform as a group. Therefore, the platform must first be deployed on the sea surface, before installing the turbines onto the platform. The platform consists of a number of hollow scaffolds, adjusted according to size, shape, and hollowness, for controlling buoyancy strength and overall robustness of the platform structure. Swing between the scaffolds is allowable; however, the overall amplitude of the whole system should be limited to a small range to prevent the turbine groups from violently changing their relative positions [35]. The platform deploying procedure also strongly depends on the velocity distribution of the ocean current. Therefore, it is more appropriate to deploy the platform farther offshore. These deploying methods and operating procedures need to be innovated, so some modeling experiments must be conducted before deploying.
2. Platform anchoring: after deploying the turbine-platform system, the anchor chains will be secured into the seabed at a depth of hundreds of meters. This step is the most important for construction engineering of the Kuroshio power plant. Each platform area may be hundreds of square meters, on which tens of turbines may be installed. Since each turbine is subjected to enormous drag from the flow, the dynamic response of the platform will also be quite large. Therefore, the number of anchor chains moored into the seabed should not be specified to improve overall structure safety [36]. Because the degree of freedom of the incline angle of the chain is generally large, it is not necessary to accurately demand the position, number, and tilt of the anchor chains. The only requirement is firmly securing the platform to the seabed. The design methodology for this technique is now quite well developed.
3. Structure design of the whole system: the first step of the mechanical analysis of the whole system is to take one platform as the main unit, and then neglect the interaction between platforms. Since a unit comprises turbines and a platform (made up of scaffolds), the flow energy captured by the turbines transfers to the platform, which the anchor chain eventually absorbs. Subjected to such mechanisms, relative motion between the platforms and the turbines will inevitably occur, so that the vibration amplitude of the motion must be limited to be as small as possible for avoiding serious damage. Therefore, the analysis will focus on predicting mechanical behaviors (such as vibration, swing, torsion, or deformation) of the whole structure [27,37,38]. The analytical results will serve as the guide for mechanical design of the scaffold, anchor chain, connectors, and other parts, and should provide sufficient information that improves the stability and lifetime of the whole system. To validate the theoretical prediction, the scale-down modeling tests, if possible, should be done in advance.
4. Undersea cables and power-transmission engineering [39]: selecting the type of power transmission (either AC or DC) should be decided first before any further design for the electricity system. The other important works for this engineering include (1) deciding the voltage level for transmission, (2) the plan for maintaining voltage using the power pooling system when an accident occurs, (3) assessing the location of marine and terrestrial transformer stations. The location substation will affect the construction cost of the power plant, so this plan must implement the evaluation of relevant issues in the beginning. On the other hand, the selection of the power transmitting type greatly influences not only the efficiency and capacity of transmission, but also on the construction costs of the power system. This is a trade-off problem. The plan must implement

optimal cost estimation based on the difference between AC and DC transmission in the power scale of the ocean plant and the transmitting distance. Therefore, it is necessary to collect sufficient information for researching the characteristics of AC or DC power transmission, which will benefit the design of electricity transmission engineering. No matter what type of electricity transmission is created by the generators, the electrical currents must converge into one or a number of joints then connect to urban electric grids through AC or DC submarine cable transmission systems. The power pooling system functions as a power bus after power is generated from the generator, and to transmit the pooled power to the interconnection points of the grid. In addition to pooling the output power, this system must include the facility to switch each marine current unit, and escape functions to avoid damage due to overload and short circuit. The purpose is to cut off the electrical current when failure occurs, and to prevent or reduce the possibility of crashing the whole system due to serious impact caused by equipment failures. Moreover, the laying and routes of submarine cables should be planned according to local geological conditions. The cables should not be laid in places where earthquakes, serious landslides, or significant sliding between different areas of the seabed frequently occurs. Finally, power-transmission engineering also affects the design methodology of the floating platform. Conversing energy on the platform and then transmitting it through the cable to land is a seemingly more efficient method.

4. Environmental assessment and geological survey

Environmental assessment is essential to the construction of the Kuroshio Current power plant, and all the related technologies are known and feasible. However, if the assessment and relate investigation are not clear enough, the damage on environment sustainability can be serious. Through preliminary assessments, three kinds of investigations need to be done before engineering work begins: (1) geological investigation of the seabed; (2) marine ecological investigation; (3) surveys of ancient Kuroshio and geological stability. The following elucidates the details.

4.1. Geological investigation of the seabed

Taiwan is located at the convergent zones of plate movement so that seismic activity frequently occurs, resulting that eastern Taiwan is an earthquake-intensive area. For the earthquake with its epicenter located near water, the induced crustal dislocation not only may cause a tsunami but also may trigger submarine landslides and turbidity, which may in turn destroy seabed facilities. For example, in 2006 the earthquake occurring in Pingtung (a county in Southern Taiwan) not only pulled apart two international cables across the Pacific Ocean from Fangshan to Pingtung, but also broke six overseas cables in Southern Taiwan due to undersea turbidity. This accident severely affected Internet communication from Asia to the rest of the world. Therefore, the purpose of geological investigation is to not only search for a suitable terrain where the turbine-platform system can be anchored firmly, but to also look for an appropriate geological structure to avoid possible collapse caused by earthquakes or other geologic hazards. Based on this purpose, the geological investigation shall be executed on two levels: (1) the extensive regional investigation and (2) the local investigation for the anchoring zone [40].

Regional investigation includes the following methods [39]: (1) Oceanographic and geophysical surveys: the multi-beam sonar and multi-channel scanning system is employed to investigate the topography, structure, and sedimentary composition of the seabed to predict possible geological disaster, such as an undersea landslide. (2) Earthquake monitoring and potential analyses of seismic disaster: these methods include comprehensive data analysis of ancient seismic history, real-time undersea earthquake monitoring, modeling analysis and prediction for earthquake potential, spectral analysis of marine seismic data, positioning of undersea earthquake location, understanding the formation mechanisms of the earthquake, inverse engineering for stress distribution of regional geology, and so on.

The investigation for geology in the anchoring zone includes:

1. High-resolution precision investigation of the seabed: this mainly includes (1) using the multi-beam sonar to map the topography and to preliminarily classify the geology of the seabed; (2) employing side-scan sonar to map the landscape, and using the reflection method to measure the thickness of the sand or mud layer on the surface of the seabed or examine signs of any collapse and dislocation; (3) using low-frequency, high-resolution sonar to scan the geological structure of the seabed surface layer, to complete the continuous-strip diagram showing the original seismic profile in digital indices, to identify or note major stratigraphic continuities or geological properties.
2. Geological characteristics of the seabed and base rocks: this includes sampling and analyzing sediment from the cores of rocks.
3. Physical and mechanical properties of material compositions: this includes a widespread regional geological survey for the physical and mechanical properties of geological materials, used to analyze the configuration, group number, spacing, and site of the discontinuous section. Considering the enormous flow thrust imposed on the turbine-platform system, this study adopts piling in anchor engineering. The geological information at anchor sites is quite important to this engineering.

4.2. Marine ecological survey

The ecological system in eastern Taiwan waters is typically an ocean ecosystem. Due to the Kuroshio influence, the water is clear and warm, forming a broad and diverse marine environment, making this an area with rich and varied marine resources. Migratory fish include flying fish, dolphins, bonito, tuna, swordfish, sunfish, whale sharks, and other resources. In addition, various kinds of reef benthic fish frequently appear on the waters, indicating that fish productivity is rich enough to support the survival of many large animals, such as whales and dolphins. To manage marine ecosystems, we have to understand the important members of the food chain in the water [41]. Plankton is not only a good indicator for environmental change and disturbance, but also provides important information for fish conservation and ecological management, because it is the most essential member of the food chain.

By setting up the Kuroshio generators in this area, the impacts of related engineering on the ecology include three parts: the ocean ecosystem, fishery resources, and the benthic ecosystem. The following discusses the ecological investigations of the three parts.

1. Ocean ecosystem: the main work is to investigate two important components of the food chain in the ocean ecosystem of Green Island, namely, zooplankton and fish larvae. First, we monitor the productivity and the community structure of zooplankton, as an indicator that assesses the impact of the Kuroshio plant construction. Second, we investigate the distribution and composition of larvae fish communities to monitor the abundance and the community of coral reef fish [42]. Sampling is the first time in the monitoring process. Then the sample is identified in the laboratory, and finally biological cluster

information is analyzed via multivariate statistics, which determines the impact on ecology by the power plant set up.

2. Fishery resources: the data obtained by fisheries along the coasts of Green Island, Taitung County, Cheng Kung, and Tomioka is collected and statistically analyzed, as the projected catch and status of fisheries in these waters. In addition, to ensure the accuracy of data and carry out systematical collection, we sample four or five anglers in each fishery, who often fish in this area. The items caught are investigated, including the composition, number, weight, and total amount. The costs of fuel, bait, and fishing tackle repair should be accounted for. The analysis of these data can give a practical indicator of fishery resources in this water.
3. Benthic ecosystem: research on the benthic ecosystem in the waters of eastern Taiwan is limited. Except for shallow-water coral reefs, the research for the ecosystems below 30 m deep is rare because of the expansive cost. The lack of equipment and labor to implement the study of deep-sea ecology is another main reason. Therefore, after selecting the power plant locations, the survey of the benthic ecosystem near the sites is investigated in detail through the assistance from foreign professional institutions, such as JAMSTEC of Japan.

4.3. The ancient Kuroshio and geological stability

Two effects probably shatter geological stability of the seabed: (1) the erosion of the benthic current and the turbidity current; (2) the undersea slumping and collapse caused by earthquakes. The two effects may damage the submarine cable or other related equipments. Thus, for selecting sites, we should seriously investigate the stability of benthic geology in the Kuroshio water [43] to determine the regions where turbidity currents may occur or pass through. This research first applies the box-rock-core sampling of the matrix grid on some concerned areas, to make high-resolution X-ray photography for rock cores, and finally analyzes the composition, age, and size of sedimentary particles.

Dating techniques include dating with lead 210 and cesium 137, supplemented by the accelerated mass spectrometry analysis of carbon-14 dating. Such research helps to determine the geological state such as sediment, erosion, benthic currents, turbidity, and other information, which greatly help in site selection and planning of the cable-laying route. Moreover, this work benefits in understanding seabed stability nearby the plant, and assesses the threat caused by a submarine landslide. In addition to the method discussed earlier (i.e. using undersea sediments to study turbidity), we also use the geometric ridge structure of the porous coral growing in the intertidal zone to identify whether Green Island has experienced uplift or subsidence of tectonic movement in the past hundreds of years. This method indicates long time (hundreds of years) stability of the volcanic cone of Green Island [44], to re-establish the influence of past tectonic activity and deduce the possible times of ancient earthquakes.

5. Planning a 30 MW pilot power plant

Kuroshio power, a renewable energy of excellent quality, has many competitive advantages from various aspects: (1) affects on environment: no carbon emission, no pollution, and no waste; (2) requirement of fuel: no need of fuel; (3) public acceptability: it is a renewable energy, and is a reward object of the world; (4) advantages over other renewable energies: such as continuous power supply (unlike intermittent wind or solar only available on sunny days) and high capacity factor (about 0.3 for wind or solar energy, but 0.7 for Taiwan Kuroshio); (5) techniques required in plant engineering: all techniques have been maturely developed without needing any further in-depth research or implying fatal technical bottlenecks. The entire cost is relatively low if the plant is successfully established (see Appendix D: analysis of construction cost of the Kuroshio power plant).

The first power plant could be located in the waters between Green Island and Taitung because the Kuroshio flow accelerates in this area. The thrust of the Kuroshio is so strong that a higher deployment density of turbines is allowable. If the turbines are deployed in an extent of about 10 km wide with a lateral interval of 0.1 km, the number of turbines for each section will be 100 units. According to the calculations with the flow over 0.7 m/s, if the power capacity of each turbine is 2 MW and the efficiency is 50%, the converted electricity for each section is 0.1 GW. Furthermore, assuming that the distance between sections is 1 km, we will obtain a total power capacity of 2 GW over a distance of 20 km (i.e. an area of 200 km^2). In general, the capacity factor (availability) of the Kuroshio plant can be up to 70%, so the annual electricity generation will reach 12.26 TWh, implying that it is an excellent power plant. The aforementioned estimate of deploying density (10 MW/km^2) is quite conservative. Promoting turbine performance will double turbine density, as soon as the flow characteristics of the Kuroshio Current can be precisely calculated.

5.1. Overall parameters of project

The following data, estimated from the viewpoint of investors, are related to the cost of constructing a 30 MW pilot plant. All the logics and sources used to calculate the data are derived or obtained after discussions with related industries and authorities. However, these estimates would become feasible only after the detail contents are modified according to actual situations.

1. The capital of construction: about 3.0 billion NTD (new Taiwan dollar, 1 USD $\sim$ 32 NTD).
2. Investment proportion: 2.0 billion NTD from enterprise (67%, can be loaned), 1.0 billion NTD from government and state-owned enterprises (33%).
3. Shares of the company:
   - 10% (R&D technical shares) owned by the R&D team (R&D main power) of the Kuroshio power generation.
   - 20% (cash investment shares) owned by the local power companies (need to rely on Taipower grid for a parallel power generation).
   - 13% (cash investment shares) owned by the Executive Yuan Development Fund (need the government policy endorsement).
   - 50% (cash investment share) owned by the enterprise group (business entities).
   - 7% (patented technology shares) for generator, anchoring systems, or inventors of marine engineering technology.
4. Plant preparation: need 1–2 years for preparation works, which includes unit testing, plant engineering, environmental and risk assessment, site selection, personnel training, laws and regulations; total funds invested is 250 million NTD.
5. Plant engineering: need 3–4 years to finish the engineering works, a total investment fund of 2.3 billion NTD.
6. Power plant operations: start up the so-called "Taiwan Kuroshio Power Company", with 450 million NTD for operation.
7. Operation income:

- Sales income: 30,000 kW $\times$ 365 (day/year) $\times$ 24 (h/day) $\times$ 0.7 $\times$ 2.8 (NTD/kWh) = 514.5 million (NTD/year) (assuming capacity factor = 70%, purchase price per kWh = 2.8 NTD).
- Carbon trading income: annual power generation kWhs = 183.75 million kWhs, the amount of carbon emission per kWh = 0.8 kg, emission credits = 147,000 tons per year, 1 ton of

carbon = 20 USD, carbon trading income = 2.94 million USD (about 94.08 millions NTD).

- Operation expenses (in the first 5 years): fuel = 0, maintenance = 20 million NTD dollars/year, Personnel + Insurance + loan interest $\sim$ 100 million NTD/year (should be evaluated carefully).
- Annual net income = 488.58 million NTD.
- Payback period = 6.2 years.
- Plant life = 20 years.

5.2. Key technologies to master

1. Forecast capability of the Kuroshio flow: Developing a global ocean analysis program and simultaneously obtaining reliable marine data from satellites at any time is necessary. The purpose of developing a self-owned program is to improve efficiency of Kuroshio power and to meet basic requirements of a high-quality power plant.
2. Design of turbine generator: Sea turbines consist of four main types, including 53 models of sea turbines, in which 16 models have been tested in the sea, while 12 models are for scale-down model testing. Although most of these turbines are suitable for shallow water, they are not difficult to change into deep-sea models because the principle behind the design methodology is the same (see Appendices A and B).
3. Design of anchoring system: After deciding the turbine model, the static and dynamic analysis for tri-axial stress and torque must be done. The analysis results will be used to design the anchoring system based on the existing techniques. To validate the design, we must first test the scale-down model in the laboratory. If the technique is feasible, the actual turbine group with the platform will be tested in the sea.
4. Techniques in marine engineering: these include the design of a deployment procedure for turbines, generators, transformers, and cables, planning a maintenance procedure, and the design for constructing vessels and working platforms.
5. Design for power plant operation: includes standard operating procedures, maintenance specifications and laws, plant security, ecological conservation, and so on.

The above first four techniques have been completely developed. Early development must cooperate with foreign technical companies. After the first power plant successfully runs, subsequent works, such as site selection, manufacturing equipments, and plant engineering can be completed independently.

5.3. Preparation work: 250 million NTD, 1–2 years

1. Site selection: Investigating the current and geological features in the waters between Taitung and Green Island. Finding an area of one square kilometer to deploy 30MW turbine groups (about 25 units, divided into 3–5 groups).
2. Turbine and anchoring system selection: From the existing technologies, select the turbines and anchoring systems suitable to the flow characteristics and geology of the seabed in the waters of the Taiwan Kuroshio. The detailed procedures include mechanical analysis, designing a power generation configuration, maintenance, and scale-down model experiments.
3. Marine engineering programming: (1) Cooperate with consulting companies, such as Sinotech, China Engineering Consultants, and so on. (2) Seek assistance from international maritime engineering companies, such as Shell, Chevron, Worley Parsons, etc. for designing marine engineering procedures and other related issues such as rigs, drawbridge, and working platform.
4. Environment and risk assessment: Take 2 years to study the environmental impacts (ex. the effects of ecology, marine, shipping line) and to assess the risk of plant and operation (such as the effects of earthquakes, typhoons, climate, policy, economy, etc.).
5. Formulation of rules and regulations: Invite the Executive Yuan (i.e. the highest level of the executive branch in Taiwan) to formulate relevant laws and regulations especially for "Kuroshio development", and to draw up regulations and ordinances related to incentives and subsidies.
6. Business model of power plant: Develop a business model similar to those regulated by the Independent Power Plant Regulation of Taiwan.
7. Training for engineers and skilled persons: Develop a constitution for training basic personnel and staff.

5.4. Construction: 2.3 billion NTD, 3–4 years

1. Site selection: The following lists the important considerations in priority order: (1) near coast; (2) shallow seabed; (3) stable flow rate; (4) strong flow speed.
2. Turbine generators: considerations in priority order: (1) Simple structure and easy to maintain; (2) high mechanical stability (robust) and long lifetime; (3) high efficiency; (4) low cost.
3. Generator inductor (gearbox): Adopt a gearbox with a permanent magnetic generator to avoid frequent repair.
4. Power-transmission cable: Adopt a deep-sea floating cable, such as a 69 kV XLPE Power cable.
5. Electricity adapter: Transmit 30 MW power from offshore to the Taiwan Power Company substation, a voltage of 345 kV will be adapted for use in Taitung City.
6. Floating structures: Adopt floating bodies of a streamlined structure with the ability of enduring deep-sea high pressure, and capable of lifting and sinking to adjust the depth, with an elastic anti-shock anchoring system.
7. Professional construction for deep-sea anchorage: Adopt deep-sea anchoring equipments with a total weight of 20,000 tons for construction.
8. Management system: Adopt deep-sea surveillance management systems similar to VPS, INTER OCEAN, DGPS, ROV, or SEA POWER (William Huang 2008, private communication).

5.5. Public relations and marketing

The success of this project depends on the assistance of central and local governments, the recognition by local residents, the people's support, and a relationship between various types of media. The following describes related works in details.

1. Central government (1): the Ministry of the Interior should grant the right of mining exploitation as "the Kuroshio power development permit."
2. Central government (2): the Ministry of Economic Affairs must grant the business license as "the Kuroshio power business permit" (IPP has "private power industry" standards).
3. Central government (3): the Department of Defense should grant the "Sea exploration permit" since the data of offshore ocean currents and seabed are national defense information.
4. Local government (1): the licensing of land-based plants (such as personnel capacity of power plant operation and power control, and the required land for a substation).
5. Local government (2): the permits of port facilities and space (equipment and rigs of plant maintenance require port space and facilities).
6. Local government (3): appropriate compensation for livelihood of anglers in Taitung based on the income of fishermen over the past 10 years. Otherwise, the government should develop

industries or businesses associated with the Kuroshio power plant to benefit the township.

7. Legislature: renewable energy development regulations should include the Kuroshio power, such as subsidies and guaranteed purchase price, etc., and energy tax legislation should include incentives for generating renewable energy.
8. Local councils: the Kuroshio power plant should receive help for developing local industries, such as Kuroshio tourist and recreational facilities of the submarine power plant, the Kuroshio power plant security industry, recreation industries of the Kuroshio waters (ex. recreational boats), and so on, all of which can promote the local economy with enterprise investments. Such investment requires frequent communication and long-term cooperation with the local gentries.
9. Marketing: although the power generation enterprise is no longer exclusive today, it is difficult to enter because the technical threshold is high and the financial supply needs to be sufficient. Since the lifetime of a power plant is more than 20 years, the plan needs to consider long-term business and operation. Industrial energy is a long-term business with stable profitability, but it depends on national policy (ex. California has introduced a free electrical market, but the Enron scandal occurred). The more cautious the plan, the safer it will be.

5.6. Possible problems and solutions

1. Typhoon: the turbines deployed at 30 m underwater can avoid the impact of billows of 10 m high due to typhoon.
2. Earthquakes: a multi-point anchoring method with a floating flexible platform can reduce the influences of landslides and slips caused by earthquakes on the anchor system.
3. Corrosion: the degree of oxidation for machines at 30 m under the sea, without air contact on the sea surface, will greatly reduce, and thus corrosion problems are easier to handle.
4. Bio-fouling: since undersea sunlight is weak at 30 m, except for some kinds of large breast-feeding fishes, few sea creatures live there, so the problem of biological attachment should be ignorable.
5. Kuroshio stability: the Kuroshio flows north along the eastern coast of Taiwan with few swing phenomena. The flow is strong and stable most of the time, except in the winter when the flow velocity decreases from the impacts of northeast monsoons.
6. The government cooperation: since the Ministry of the Interior owns mining rights, the Ministry of Economic Affairs owns business rights, and the National Defense Department owns the topography and geological information of seabeds, related authorization needs the cooperation of cabinet-level policies.
7. Ecological protection: Turbines are deployed 30 m undersea, in which the plankton and fish are rare (because of the high temperature of Kuroshio). Moreover, the use of sonar can expel large fish such as dolphins. The impact on ecology only appears during construction; therefore, ecology rehabilitation should be quick after construction.
8. Slowing down the Kuroshio flow: The influence of power plant engineering depends on the driving force strength of the Kuroshio flow and the deployment density of turbines. Thus, a detailed analysis of the flow features in the area near the plant, and the deployment form and density of turbines is necessary for design.
9. Site selection: (1) near coast: low cost (2) shallow seabed: low cost (3) stable flow velocity: stable power output and easy maintenance (4) high flow speed: great power.
10. Strategy for site development: the plan must obtain the rights for developing high-quality sites before developing the Kuroshio power plant.

5.7. Other relevant analysis and research

The following describes several issues related to plant operation.

1. Finance and market: Includes construction cost analysis, operational cost analysis, cost risk analysis, capital acquisition, customer groups, power purchase, and so on.
2. Risk assessment and management: Includes political risk (changes in renewable energy incentives and subsidies, implementing carbon tax or energy tax, permits for developing inland and waters, local politics and interest groups), natural disasters (typhoons, earthquakes, climate change), marine life destruction (biological attachment, impact of fish, seaweed fetters), environmental risk (Kuroshio disappeared, weakened, and shifted), financial risk (changes of lending measures, structural changes in the field of public and private investment, impact of energy price fluctuations), man-made disasters (fishing vessels trawling damage, terrorism, submarine strayed into), the risk of war, and so on.
3. Formulation of relative regulations: The contents of many laws and regulations need to be studied to formulate new provisions, such as mining laws and regulations to develop Taiwanese waters, the Kuroshio Energy Development Act in public waters, port use and land-acquisition-related laws, Act of obtaining relevant information near the seabed, Act related to electricity sales (Renewable Energy Development Act, in ocean part), incentives or coercive measures to encourage energy-intensive industries to invest renewable energy, and the development of other laws.
4. Long-term assessment: Long-term observation is necessary to assess possible changes in government policies, such as a renewable energy policy, energy pricing policy, carbon tax and carbon trading system, environmental ecological policy, ocean development policy, economic and financial crisis, laws and regulations of private power plants. In addition, considering global energy technology development and national energy policies is essential.
5. Assessment of environmental impacts on the site area: Both stages of construction and operation need detailed surveys and assessments, such as the impacts on vessel movements (including merchant ships, fishing boats, warships, and so on), the effects on the Kuroshio flow, the effects on the sea and seabed ecology, the impacts on the daily correlative operation in the eastern coast, etc. Other impacts are the turbine resistances to the Kuroshio Current, the plant construction impact on the submarine ecology, and the power plant operations impact on the marine ecology.

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Appendix A. List of the world's major turbine generators

There are totally 16 prototype testers:

Horizontal axis	Atlantis Resources Corp — Solon Clean Current Power Systems — Clean Current Tidal Turbine Hydro Green Energy — Hydrokinetic Turbine Marine Current Turbines — Seagen & Seaflow OpenHydro — Open Centre Turbine Robert Gordon University — Sea snail Tidal Hydraulic Generators Ltd. — Tidal Hydraulic Generators UEK Corporation — Underwater Electric Kite Verdant Power — Various
Vertical axis: standing type	GCK Technology — Gorlov Turbine (Turbine component suppliers) Ponte di Archimede — Kobold Turbine Tidal Energy Pty Ltd. —DHV Turbine University of Naples — ENERMAR (Predecessor of MYTHOS)
Vertical axis: lying type Reciprocating type	Ocean Renewable Power Company — OCGen Pulse Generation — Pulse Generators The Engineering Business — Stingray
Other	Atlantis Resources Corp — Aquanator & Nereus

There are 12 scale-down testers:

Horizontal axis	Teamwork Tech — Torcado University of Southampton — Southampton Integrated University of Strathclyde — Contra-rotating marine current turbine
Vertical axis: standing type	Blue Energy — Blue Energy Ocean Turbine (Davis Hydro Turbine) Neo-Aerodynamic Ltd. Company — Neo-Aerodynamic Neptune Renewable Energy Ltd. — Proteus New Energy Crop. — EnCurrent Vertical Axis Hydro Turbine
Vertical axis lying type	Hydro-Gen — Hydro-gen HydroVolts — Vertical axis, variable pitch tidal turbine Ocean Renewable Power Company — OCGen
Reciprocating type Other	BioPower Systems Ltd. — bioStream Vortex Hydro Energy — VIVACE (Vortex Induced Vibrations Aquatic Clean Energy)

Note: Currently, there are 25 other types in the conceptual design stage without testing.

Appendix B. Performance summary of four different types of ocean current generators

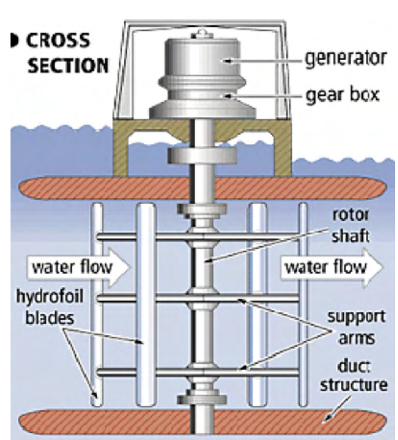
B.1. Horizontal axis: Marine Current Turbines — Seagen & Seaflow: http://www.marineturbines.com/

The company is based in the UK. In May 2003, SeaFlow (a single turbine of 300 kW) was set up in Lynmouth, on the North Devon Coast of the United Kingdom. In 2008, Strangford Lough of Northern Ireland successfully set up SeaGen (a dual turbine of 1.2MW). The generator has a link to the local grid, running approximately 18–20 h/day.

Cooperating with Queen's University and local institutions, the company is also devoted to a series of ecological and environmental impacts via the numerical simulation of large-scale ocean currents. In view of engineering technology, this company can be an indicator of today's ocean current power generation. The anchoring system used is the piling type, suitable for shallow seabed waters where geological strength is high and homogenous. Currently, two projects are ongoing. One is the construction project for a power plant of 10.5 MW, located in Saint George's Channel (between the UK and Ireland). Another is the plan for demonstrating the performance of power plants located in Nova Scotia province and the British Columbia province of Canada, respectively.

B.2. Vertical axis of standing type: Blue Energy — Blue Energy Ocean Turbine (Davis Hydro Turbine): http://www.bluenergy.com/

The company is located in Canada. The main part of their machine is the Davis Hydro Turbine, developed by modifying the design from the patent owned by the French inventor Georges Darrieus in 1927.



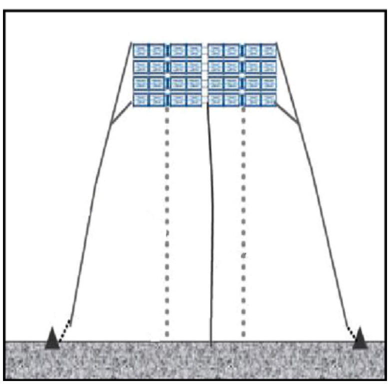
The company integrated a number of research groups, which have used Davis Hydro Turbines as an ocean current

turbine. To anchor this machine, several approaches can be adopted, ex. floating with cables, fixing with a heavy base, and combining with civil engineering structures. The desired capacity of a single generator is about 10 kW.

Recently, there are three major projects being implemented or under discussion. The first is a demonstration power plant located on the coast of British Columbia province, Canada, with a power capacity of 20–25 kW; the project is expected to be used as a system integration for both hydrogen production and fuel cell. The second is the Retrofit Bridge Project located in Tacoma City, Washington state, the United States, which will set up Davis Hydro Turbines under the bridge. The third is a tidal stream power project of 2.2 GW in San Bernardino Strait, the Philippines. However, the information of the three plans has not been updated yet.

B.3. Vertical axis of horizontal type: Ocean Renewable Power Company — OCGen; http://www.oceanrenewablepower.com/home.htm

The company was established in the U.S., funded by Paul H. Wells in September 2004, which then finished the turbine unit design (Turbine Generator Unit, TGU) in 2006. Finally, the performance test was conducted in April 2008.



The type is characterized by the number of turbine units that are adjustable to adapt to various distinct environments without changing the size of the turbine. This characteristic not only significantly reduces the cost, but also widely increases the applicability. In addition to the power generation for ocean currents, the machine can be used in rivers and tidal flow. The figure shown here is the configuration for the ocean current power generation (the cut-in flow speed is 0.5–1 m/s).

Currently, there are projects under contact or ongoing in Florida and Maine (Western Passage, Cobscook Bay) and Alaska (Cook Inlet).

B.4. Reciprocation type: The Engineering Business — Stingray: http://www.tidalenergy.eu/engineeringbusiness_stingray.html

The company, a branch of the IHC Group, the Netherlands, is based in the UK. The equipment uses a hydraulic system to control the angle of wing attack, resulting in reciprocating actuation; this reciprocating action then pushes another set of hydraulic generators to generate electricity.

The design started in 1997, and a generator prototype of 150 kW was completed in 2002. During July to September 2003, the tests were done in Yell Sound of the Shetland Islands, United Kingdom.

The generator is suitable for shallow water, and the anchoring means can be gravity basement or pile positioning. However, the swing range is large, and may affect the original pre-existing water activities (shipping, fisheries, ecology, etc.) The efficiency is significantly influenced by the direction and velocity of the ocean current, and reached 25–30% by following the direction of flow with low velocity (i.e. the flow flows from inside to outside, as shown in the upper diagram).

Appendix C. Characteristics and comparison of vertical axis turbine

The turbine of vertical axis is divided into two kinds according to the shape of the blade: the Darrieus type and the Gorlov type. Performances are as follows [17].

C.1. Darrieus vertical turbine generator:

A number of wing-shaped blades are arranged perpendicularly to the rotation axis of this kind of turbine. The patent was designed by Georges Darrieus, a French aerospace design engineer in 1932. In the vertical axis of rotation, a double-speeding device and generator can be placed above water, thus excluding the problem of flooding and also simplifying maintenance procedures; another advantage is that Darrieus turbines do not account for the flow direction of water. Thereby, all waters make the turbine rotate in one direction, so it is suitable for capturing tidal flow energy, which frequently changes directions. However, this propeller-type turbine has to be installed in a double-speeding device and generator, to adapt to the tidal direction change.

However, pulsate often occurs to the Darrieus turbine during rotation, because when water flow changes direction, its operation angle with the blade changes all the time, leading the combined force and torque imposed on the shaft of the Darrieus turbine into a period change with time, thereby, affecting its useful life. In addition, vibrations on the Darrieus turbine likely cause fatigue on the parts,

which is the main reason why the Darrieus turbine has not been widely used.

This shortcoming can be overcome by changing the vertical blade into a screw blade, thus boosting overall turbine efficiency by 35%, which is higher compared to other non-pipe-types of water equipment.

C.2. Gorlov helical turbine generator:

The Gorlov helical turbine, also a vertical axis turbine, is currently used by the tidal power plant of SHIWA 200 MW in South Korea, and is being considered for power generation in the Gulf Stream. This kind of helical turbine, a reactive cross-flow machine, was invented in the mid-nineties, and tested in many laboratories, including the University of Michigan, Cape Cod Canal, Maine, and the Uldolmok Strait of South Korea. In these tests, the efficiency of this three-screw blade turbine in the free flow can stably reach 35%, making its performance one of the best in hydraulic turbines. The helical turbine can capture the current energy of small velocity but high flow, and the cost is lower due to its simple structure.

Different from the Darrieus, the Gorlov turbine blade is spiral, which can produce high torque in a low flow rate. To reduce or eliminate the pulsate of a turbo-machine, all spiral blades must be covered on the surface of the rotating wheel, and the appearance of all blades projected onto the plane will look like a three-dimensional ring, and the ring width is equal to the blade thickness. The turbine can reach kinetic balance only when the spiral is symmetrical with the axis. The combination of torque and thrust is transmitted to the turbine axis through the blade to drive the turbine to spin.

C.3. Comparisons between the Darrieus straight blade turbine (hereinafter referred to as turbo-D) and the Gorlov spiral blade turbine (hereinafter referred to as turbo-G) are described below:

- The D Turbine extracts kinetic energy from the overall blades regularly impinged by water flow, while the G turbine captures energy from the end of the spiral blade.
- When rotated at high speed, the linear blade end of the D turbine could be damaged, probably because of cavitation (air blast), which often leads to pulsate and fatigue to the blade. On the other hand, the G turbine does not have such a problem, because its spiral blades are distributed around the rotating cylindrical surface, and the maximum energy in the acquisition does not require very high speed.
- The compound D turbine can be s horizontal or vertical module, comprised of s general shaft and a single generator; on the contrary, the turbo-propeller tower of the G turbine can be designed as an independent underwater power system, comprised of a single screw and a complex underwater generator. Regarding operation, more than two spirals cannot be assembled in a single system.
- As a horizontal structure, the D turbine can be operated in very shallow water, such as shallow seawater or coastal tide, while the G helical turbine cannot be operated in any shallow water.
- The D turbine is a one-way rotation machine, and more suitable to continuous tidal water, compared to the G turbine; on the contrary, if the spiral G turbine is to be used in waters with repetitious flows, an additional converter or blade adjustment is needed, thereby complicating the system and increasing the cost.

The following organizes the papers relative to sea turbines with vertical axis:

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- Zanette, J., Imbault, D., & Tourabi, A. 2010 "A design methodology for cross flow water turbines", Renewable Energy, 35, 997–1009.

Appendix D. Analysis of the building cost for the Kuroshio Current power plant

Here, we take the scale of 100 MW-class of a "commercially running power plant" as an example, making the building cost structure of the Kuroshio Current power plant as follows. Here, the cost is analyzed on the premise that the plant is already commercially operated and established, while the cost analysis of a pilot-based plant is different.

In general, the cost structure of a tidal power plant is divided into six parts (Please see Fig. D1): turbine systems, anchoring systems, submarine cables, turbine installation, cable installation works, land-based power plant, and grid construction. The first three are machinery and material costs, and the latter three are project costs. If the tidal power plant is constructed on seven different sites, the turbine cost is about $500–900/kW (specification level of the turbine is determined by the ocean current situation), the construction cost of the anchoring system erected with turbines is about $500–1000/kW (level of structural specification is determined by the geology and depth of the seabed). The costs of the cable material are not high and are determined by the distance between the coast and the site, and the erection cost of the turbine is about $200–600/kW and determined by the location of the site and the depth of the seabed, the submarine cable-laying project cost is about $150–900/kW and is

determined by the factors of seabed depth, geology, distance to the coast, etc. The cost of the land-based distribution equipment is small and determined by the distance between the site and downtown. Overall, the construction cost of the tidal power plant is about $2000/kW. These are construction costs of a commercially operational power plant (with a generation capacity of 100 MW or above).

We take this standard to estimate the construction cost of the Kuroshio power plant of 100 MW, which is about 6.5 billion NTD (1 USD is equal to 32 NTD). Other estimates of the operation cost are detailed as follows:

- Annual kWhs of electricity generation: 100 × 1000 kW × 365 day/year × 24 h/day × 0.7 = 613.2 million kWh/year (assuming capacity factor is 0.7).
- Annual income from electricity sales: 613.2 million kWh/year × 2.8 NTD/kWh = 1.717 billion NTD/year. (It is assumed that the acquisition price guarantee is 2.8 NTD/kWh, which refers to ROC renewable energy development regulations, while the acquisition price guarantee of offshore wind is 2.8 NTD/kWh.)
- Annual revenue to sell carbon emissions quotas: 613.2 million kWh/year × 0.8 kg/kWh × 20 U.S. dollars/ton × 32 NTD/USD = 314 million NTD/year. Assuming carbon emissions per kWh is 0.8 kg, and purchase price is 20 U.S. dollars per ton of carbon (the European futures market price in 2008).
- Plant operation costs: including maintenance (maintenance is free at first 5 years), loans and interest, personnel, general expenses, about 200 million NTD/year (needs to be carefully assessed).
- Annual net income = 1.717 + 0.314 − 0.2 = 1.831 billion NTD.
- Payback period: 6.5/1.831 = 3.55 years.
- If the plant life is 10 years, electricity generation cost for every kWh = 6.5 billion NTD/(10 × 613.2 million kWh/year) = 1.06 NTD/kWh, which is very competitive.
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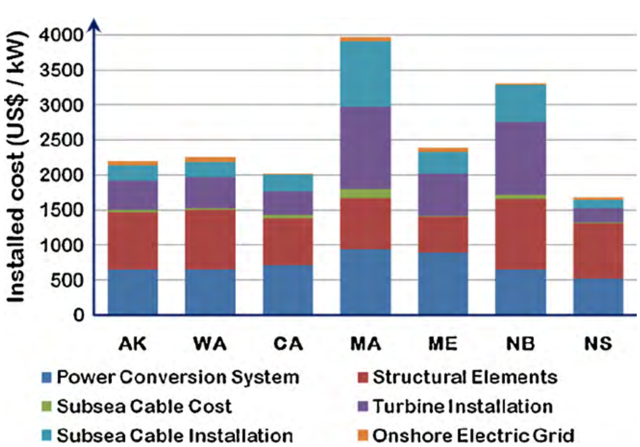

Fig. D1. Plant cost structure of seven plants in North America. AK: Alaska; WA: Washington; CA: California; MA: Massachusetts; ME: Maine; NB: New Brunswick; NS: Nova Scotia (source: U.S. EPRI reports, such as the following).

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