BALANCE OF PLANT AND POWER TRANSMISSION FOR THE OFFSHORE FLOATING NUCLEAR PLANT

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ABSTRACT

The Offshore Floating Nuclear Power Plant (OFNP) concept combines two established technologies, i.e. Light Water Reactors and offshore floating platforms, to offer major potential enhancements in economics and safety with respect to terrestrial plants. A cylindrical hull-type platform, moored between 10 and 20 km offshore, houses the power module, which is connected to the on-land electric grid by a submarine cable. The OFNP concept can accommodate virtually any reactor and power cycle designs, with proper modification of the platform size. However, we currently are pursuing two designs which adopt respectively an integral PWR in the 250-350 MWe range, e.g. the Westinghouse SMR, and the AP1000, which has a rated electric power of 1100 MW. The two plants are designated OFNP-300 and OFNP-1100, respectively.

The Balance of Plant (BOP) of the OFNP converts the thermal power produced by the Nuclear Steam Supply System (NSSS) into electrical power through a conventional Rankine cycle and turbo-generator. Cooling water for the condenser is drawn from the cooler layer depths of the ocean and discharged at ambient temperature at the surface, thus reducing thermal environmental effects. Also, the power cycle can achieve higher thermal efficiencies than terrestrial nuclear power plants depending on the local temperature of the ocean and the specific design.

The BOP design for the OFNP gives rise to unique design challenges. First, space on the platform is limited, and some components such as the turbo-generator and condensers are typically very heavy and large, approaching the maximum load capacity of onboard and shipyard cranes and moving equipment; second, developing a compact but functional layout is essential to ensure ease and low cost of operations and maintenance. Electricity is generated at relatively low voltage (<30 kV), but is most efficiently transmitted at much higher voltage. Therefore, an electrical substation with its Generator Step-Up (GSU) transformer units is needed on the platform.

This paper discusses the thermodynamic design and physical layout of the OFNP-300 power cycle and the corresponding power transmission train, including the GSU transformer and the submarine cable. The Rankine cycle analysis is carried out with the support of the Aspen Plus V8.0 package. It is shown that a BOP design with a single condensing turbine achieves high thermal efficiency (>36%) and satisfactory compactness.

KEYWORDS
Rankine cycle, efficiency, transmission, submarine cable.

1. INTRODUCTION

The concept of an Offshore Floating Nuclear Plant (OFNP) under development at the Massachusetts Institute of Technology has the potential to reduce cost, enhance safety and facilitate worldwide deployment of nuclear plants [1]. The OFNP design creatively builds on two established technologies, namely light water reactors (LWRs) and floating oil/gas platforms. Several features produce a particularly attractive design. The OFNP can be entirely built on a floating rig in a shipyard and then towed to the site, where it can be anchored between 10 and 20 km off the coast, in relatively deep water (about 100 m or more). Shipyard construction enhances quality, reduces construction time and provides a reliable modularization approach. Plant decommissioning is done quickly and cost-effectively in a centralized shipyard (just as for the U.S. Navy nuclear submarine and carrier fleets), so that the site can be returned to "green field" conditions after the floating platform is towed away. The nuclear island is under the water line, with easy access to the ocean heat sink; therefore, indefinite decay heat removal can be assured without external intervention. The likelihood of accidents with fuel damage and radionuclide release, as well as the need for land evacuation are drastically reduced. An underwater power transmission line connects the plant to an on-land electric switchyard. Land usage is reduced to essentially zero, the consequence of this being a substantial increase in the number of potential sites available for OFNP deployment [2]. A thorough description of the OFNP concept and design, including open issues, is reported in Ref. 1.

The OFNP main structure is a cylindrical hull-type platform with catenary mooring. A simple cylindrical, partially-submerged, floating rig, has a low center of gravity for added stability This platform design, widely used for oil/gas floating rigs, eliminates transmission of seismic loads from the ocean floor, and offers a good compromise between cost and dynamic stability with respect to waves, wind and blast [3]. The OFNP concept can accommodate virtually any reactor and power cycle designs, with modifications to the size of the platform. However, the design presented here, and designated OFNP-300, adopts an integral PWR in the 250-300 MWe range, e.g. the Westinghouse SMR [4], [5]. The OFNP-300 cylindrical hull has a draft of about 48 m and a diameter of about 45 m, the main deck is about 12.5 m above the water level and the total displacement is about 38000 ton. The natural period for heave and pitch motion of the plant is about 20 seconds, which is much lower than the period of tsunami waves; therefore, the plant rides a tsunami wave with no risk of flooding. However, the natural period is higher the range of storm wave periods, which minimizes plant oscillations during storms.

Watertight below-deck compartments house the nuclear island, the control room, the battery room, the turbine island, the spent fuel pool, the radwaste facilities, the desalination units and the condensate storage tank (CST). The watertight compartments have both vertical and azimuthal bulkheads, to ensure floatation in case of breach or accidental flooding of one level. The crane, crew living quarters, helipad, lifeboats and (non-safety) diesel generator are above the main deck. Loads and stresses over all the components must be determined in order to verify that their mechanical integrity is maintained and their relative (and often very small) tolerance ranges are respected. A further concern is the study of low frequency oscillations, in particular the effect of dynamic loads due to wave action on shafts of large turbines mounted on floating structures. This coupling between the power conversion system, particularly the turbine, and the estimated motion of the spar is emerging as a potentially important problem for the concept.

All primary system components (core, control rods, pressurizer, steam generators, reactor coolant pumps) are integrated within a single Reactor Pressure Vessel (RPV), which is located within a compact pressure-suppression containment. The reactor and containment constitute the reactor module, which is housed inside the reactor hull, within a permanently flooded compartment at the bottom of the platform. The gap between the containment and the reactor hull is normally dry, so the containment shell is not exposed to seawater. However, that gap can be flooded with seawater to provide passive containment cooling during low-probability accidents. The steam lines run from the reactor module to the steam drum and the turbine deck; the feedwater lines follow the inverse path. More details on the OFNP concept can be found in [1].

This paper presents the conceptual design of the OFNP power conversion cycle, or Balance Of Plant (BOP).

2. OBJECTIVES AND METHODOLOGY

2.1. Scope of the Work

The turbine island of the OFNP converts thermal energy produced by the Nuclear Steam Supply System (NSSS) into electrical energy through a conventional Rankine cycle that uses water as the working fluid. In the thermodynamic analysis of such systems, there are two principal figures of merit: first, thermal efficiency, i.e., the ratio of the net work to the heat added to the cycle, which is a measure of performance affecting specific capital, fuel and operating costs [6] and second, layout compactness, which is directly related to capital cost thus affecting the price of electricity.

This work explores various possible configurations of the steam cycle, with the objective of providing the best compromise between thermal efficiency and capital cost. The general features of the power transmission system, including the choice of cables and transformers, which are required to connect the OFNP to the grid, are also discussed.

It should be noted that the OFNP project gives rise to unique design challenges compared to traditional nuclear power plants. First, the space available on the floating platform is limited, since a large increase of the size of the cylindrical hull could lead to unacceptable construction and transportation costs. Turbo-generators for power production are typically very large components (shaft lengths can reach 75 m for the highest power ratings), and this is true for condensers as well, e.g. in Areva's EPR plants, each condenser unit occupies about 680 cubic meters and weighs about 1600 tons. In addition, the layout is important: a functional arrangement will enhance quality of operations and simplify maintenance procedures. Moreover, intelligent layout can help address certain turbomachinery-specific safety issues such as the protection from turbine missiles. Hence, in the context of an offshore application, space availability represents a constraint, and its management is a key point for the overall success of the design process.

2.2. Methodology and Simulation Tools

The code Aspen Plus V8.0 was used to perform the OFNP BOP analysis. It allows the creation of process models, starting from a flowsheet, describing the connections among components, and then specifying the operating conditions of such components. Flowsheets map out the entire system. They enhance the physical visualization of the process itself, illustrating all intermediate unit operations and interconnecting streams. All units are analyzed under specific operating conditions (thermodynamic properties), which are controlled by the user. Aspen Plus handles the user's input. By means of mass and energy balances, phase and chemical equilibrium equations it executes all necessary calculations needed to predict the behavior of the system and provides the results, stream-by-stream and unit-by-unit [7]. The thermodynamic properties of water were obtained from the International Association for the Properties of Water and Steam formulation of 1995 (IAPWS-95) [8]. All results presented in this paper were checked for consistency and some verified by means of hand calculations. Thermodynamic analyses were carried out for every design option, i.e. for each Rankine cycle, the working fluid properties (temperature, pressure, quality, density, enthalpy and entropy), the net power generated by turbines and required by pumps, the heat exchanged at the interface with the primary loop (entering the cycle) and the heat released to the environment (seawater) were calculated. The cycle thermal efficiency was also calculated.

3. STEAM CYCLE: DESIGN AND DISCUSSION

The two chief requirements for the BOP are (i) a thermal efficiency of at least 30%, and (ii) a turbo-generator length that is less than 45 m, and height less than 11 m, to be accommodated in the turbine hall of the platform. Other design considerations include: a layout for efficient maintenance and operations; a desire to use existing turbine models to reduce development costs; an ability to operate at 50 or 60 Hz so that the OFNP can be used in every market; a low risk of damage to critical components from turbine missiles.

This section reports several possible layouts and operating conditions of the steam cycle, designed for high thermal efficiency and low capital cost. The following assumptions were made. The heat duty (900 MWth) was chosen to represent the Westinghouse SMR design. Turbine inlet and outlet pressures are 70 bars and 0.045 bars respectively. A condensing pressure of 0.045 bars corresponds to a temperature of about 31°C. Ocean water temperature data from the ARGO observatory database [9] can be correlated as follows:

$$T(D) = -0.338 + \frac{(S + 0.338) \cdot f(D)}{1.485 \cdot 10^{-4} \cdot (S + 0.338) \cdot D + f(D)} \quad (1)$$

where S is the surface temperature (expressed in °C), D is the water depth in meters and $f(D) = 1 + e^{-0.016 \cdot D + 1.244}$. In the OFNP, cooling water can be drawn from the bottom of the ocean and discharged at ambient temperature, thus eliminating thermal pollution. According to Eq.1, assuming a surface water temperature of 25°C, the cooling water at a depth of 100 meters is 20.4 °C, sufficiently cold to allow for a discharge temperature of 25 °C and a steam-side condenser temperature of 31°C.

Typical values of 93% and 85% were employed for the isentropic efficiency of the turbine and pump respectively. Then a set of twelve different configurations were generated and analyzed first by hand calculations (Table I). Various input parameters were explored, such as evaporation and condensation pressure and temperature, number of steam extractions and degree of reheating (temperature difference between reheater inlet and outlet). A qualitative assessment of the level of complexity of the cycle was assigned to each design, according to number and size of every component in the cycle. Complexity is used here as a qualitative proxy for capital cost. The resulting ranking of the designs is shown in Fig. 1, which assigns a different color code to different conceptual approaches and indicates in green the three options that were selected for further study.

Note that steam turbines are often divided into two types: condensing and backpressure turbines [10]. In turbines of the first type, steam is condensed below atmospheric pressure: condensing turbines have a much larger expansion of the steam and a larger change in enthalpy, resulting in larger work output and greater efficiency of the Rankine cycle. In applications where efficiency is a prime consideration, such as large power plants, condensing turbines are preferred. High efficiency and power output must compensate for a more complex and expensive design. The condensation process occurs at a very low pressure, the consequence of this being a turbine with a greater number of stages, larger condenser and larger diameter pipes (due to low fluid densities). Moreover, additional equipment is needed, such as vacuum pumps for start-up operations.
By contrast, backpressure turbines are less efficiency, but more compact.

Table I. General specifications of the BOP designs considered in this study. Color code: red for single condensing turbine, orange for backpressure turbine, and blue for two condensing turbines.

Opt.	Evaporation pressure (& temp) [bar (°C)]	Condensation pressure (& temp) [bar (°C)]	FWPH (Feedwater preheaters)	Moisture separator	Reheat [°C]	Efficiency [%]	Level of complexity
1	70 (285.86)	0.045 (31.02)	2	Yes	100	36.76	Medium
2	70 (285.86)	0.045 (31.02)	4	Yes	100	37.39	Medium
3	70 (285.86)	1.100 (102.32)	0	No	No	25.92	Low
4	70 (285.86)	1.500 (111.38)	1	No	No	24.85	Low
5	70 (285.86)	1.000 (99.63)	0	Yes	70	26.62	Low
6	70 (285.86)	1.000 (99.63)	1	Yes	70	26.72	Low
7	75 (290.57)	1.000 (99.63)	0	Yes	70	27.08	Low
8	75 (290.57)	1.000 (99.63)	2	Yes	70	27.43	Medium
9	75 (290.57)	1.000 (99.63)	0	Yes	100 + 30	26.90	Medium
10	80 (295.04)	1.000 (99.63)	0	Yes	100	27.38	Low
11	70 (285.86)	0.045 (31.02)	2x2	Yes (2x)	100	36.18	High
12	70 (285.86)	0.045 (31.02)	2x4	Yes (2x)	100	36.81	High

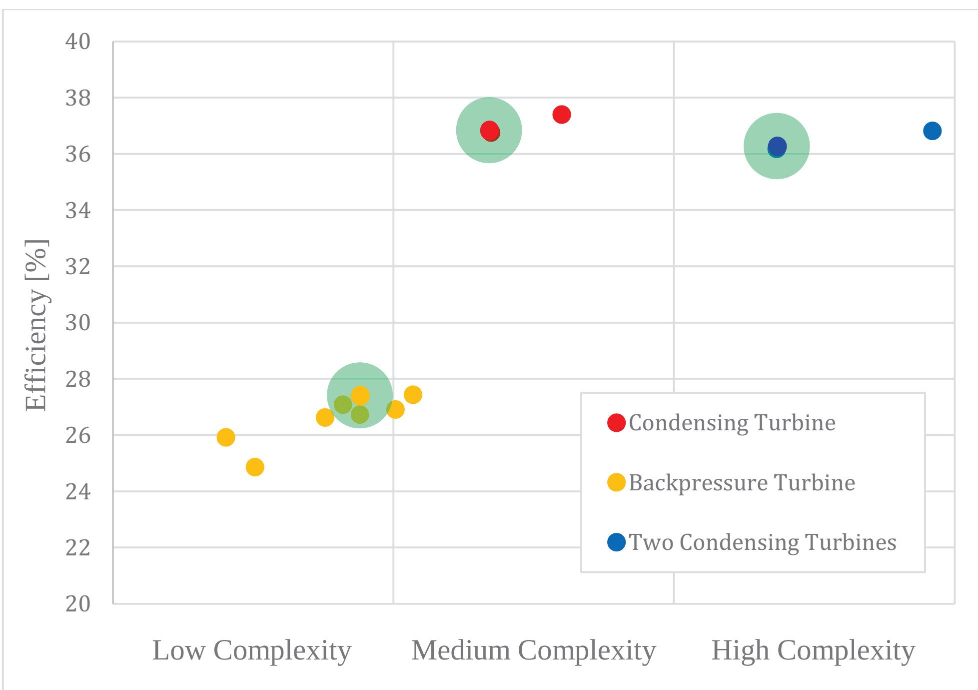

Figure 1. Design chart. Color code: red for single condensing turbine, orange for backpressure turbine, and blue for two condensing turbines. The green-circled options are those selected for further study in this paper.

3.1. Condensing Turbine

3.1.1. Single-turbine approach

A Siemens SST-4000 series condensing steam turbine was identified as a potentially viable choice. General specifications and power output match the needs of the OFNP; its design is quite flexible, so that it can be considered for various plant configurations, and it is available for both 50 Hz and 60 Hz applications. One problem is that the turbo-generator height is such that it would require raising the ceiling of the turbine deck by a few additional meters. Fig. 2 shows the layout of the turbine floor. The Aspen Plus analysis for this chapter refers to 'option 1' in Table I. The relatively small gain in efficiency that one would get by adopting option 2 in the same table, does not justify the significant increase in complexity and cost that would derive from such a choice (two more regenerative steps with two more feedwater pre-heaters). The main features of the system are shown in the plant layout below (Fig. 3). The Rankine cycle includes a high-pressure and a low-pressure turbine with steam extractions to the feedwater preheaters. In order to alleviate the problem of having moisture droplets in the last stages of the turbine (which can cause damage to the blades), the working fluid goes through a moisture separator and then is reheated after an initial expansion in the high pressure turbine. The efficiency of the cycle is improved, given that more of the heat input to the cycle occurs at higher temperature. The energy for reheating comes from condensation of a small amount of steam from the steam generator, subsequently throttled to a lower pressure level. In this study, steam is reheated to about 100°C above saturation.

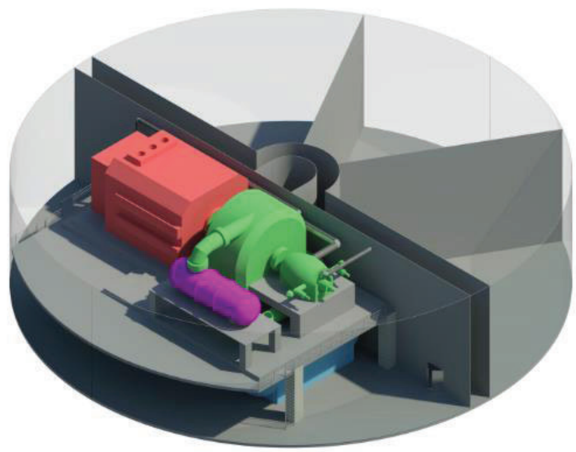

Figure 2. Isometric view of turbine sector, option 1 in Table I.

The overall thermal efficiency of the cycle is obtained as

$$\eta_{th} = \frac{\sum_{i=0}^{I} \dot{m}_i h_i + \dot{Q}}{\dot{Q}_{in}} = \frac{\dot{W}_{turb} - \dot{W}_{pump}}{\dot{Q}_{SG}} = 36.76\ \% \tag{2}$$

where $\dot{W}_{turb} = 333.625\ MW$, $\dot{W}_{pump} = 2.756\ MW$, and $\dot{Q}_{in} = \dot{Q}_{SG} = 900\ MW$. This high value of the thermal efficiency comes primarily from the low temperature achievable in the OFNP condenser which is possible because the cooling water is drawn from the cooler layer of the ocean; this is a unique feature of the OFNP with respect to terrestrial plants.

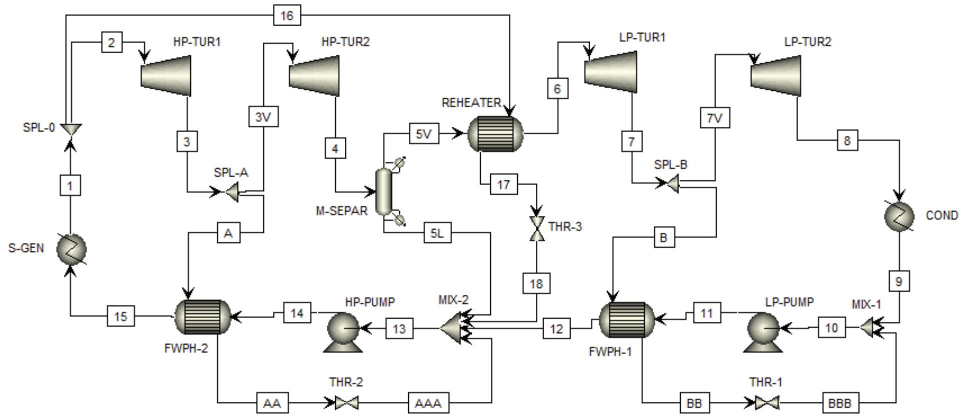

Figure 3. System layout in Aspen Plus V.8.0., option 1 in Table I.

3.1.2. Two condensing turbines

In an effort to reduce the length and height of the condensing turbine, the idea to split the heat duty over two separate turbines was explored (Fig.4).

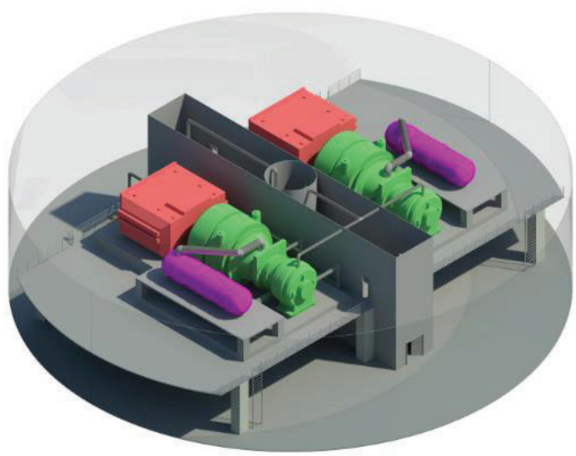

Figure 4. Isometric view of turbine sector, option 11 in Table I.

This means, in practice, to consider two loops, each processing half of the steam flow from the steam generators, the consequence being a larger number of smaller components. The level of complexity obviously increases (Fig. 1): double loop means double turbine, generator, pumps, valves and piping. This design is more expensive comparing to a single-turbine design with the same power rating. However, the turbines would be shorter in length and height, and thus easily accommodated in the current turbine hall of the OFNP platform. A further advantage is the symmetry of the overall layout: this arrangement would be, in principle, favorable in terms of structure weight balance. The two turbine arrangement affords a certain flexibility in operating the plant in partial-load mode, should that be desirable for either online maintenance or accommodation of variable load. The coupling between rotating machine and platform motion deserves particular attention for the future development of the OFNP. If this solution (two turbines) will be pursued, it could be worth considering the possibility to spin the shafts in opposite directions in order to eliminate the overall gyroscopic torque on the basement of the platform.

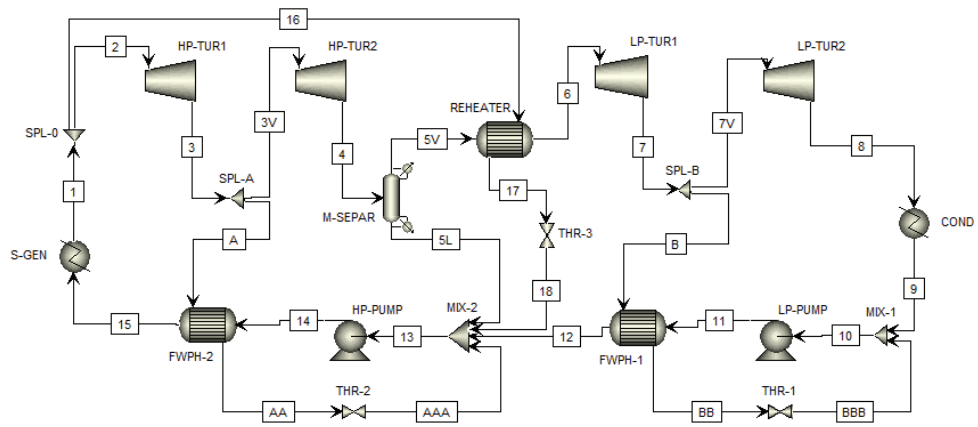

Figure 5. System layout in Aspen Plus V.8.0., option 11 in Table I.

The Aspen Plus analysis was performed for only one of the two identical loops forming the overall system. The Aspen Plus analysis for this chapter refers to 'option 11' in Table I. Fig. 5 shows that the layout of each loop: in terms of number of components, type and relative arrangement, this layout is identical to the single condensing turbine (Fig. 5). It should be noticed that a slightly smaller value for turbines isentropic efficiencies was selected (91% instead of 93%), reflecting the fact that smaller turbomachinery typically has larger relative losses.

The overall thermal efficiency of the cycle is obtained as:

$$\eta_{th} = \frac{\sum_{i=0}^{I} \dot{m}_i h_i + \dot{Q}}{\dot{Q}_{in}} = \frac{\dot{W}_{turb} - \dot{W}_{pump}}{\dot{Q}_{SG}} = 36.18\ \% \tag{3}$$

where $\dot{W}_{turb} = 164.076\ MW$, $\dot{W}_{pump} = 1.287\ MW$, and $\dot{Q}_{in} = \dot{Q}_{SG} = 450\ MW$. Thus the gross power output is 328 MW, slightly lower than for the single condensing turbine.

3.2. Backpressure Turbine

In a backpressure turbine, steam leaves the last stages of the turbine at pressure levels equal to or above the atmospheric pressure. This approach is *not* common in traditional nuclear power plant applications because it hurts efficiency. Nevertheless, it has been deemed potentially interesting in this project since it allows for a very simple and compact turbo-generator/condenser design. Compared to a condensing turbine, the backpressure turbine would be shorter axially and radially since the LP stages are eliminated, and the condenser would be smaller since the vapor density is much higher. Moreover, the vacuum pump for start-up operations would also be eliminated. The radial arrangement of the turbo-generator shown in Fig. 6 is favorable in the floating cylindrical hull geometry. Unfortunately, shifting the turbine exit pressure (thus condensing temperature) to higher values, does lead to a large efficiency drop. As a result, the net electric power produced is lower. The Aspen Plus analysis was performed only for option 11 from Table I. The Siemens SST-800 series steam turbine was chosen. This model is used for tailor-made applications. It operates at either 50 or 60 Hz, for generators up to 250-300 MW, and it can be manufactured for both condensing and backpressure applications.

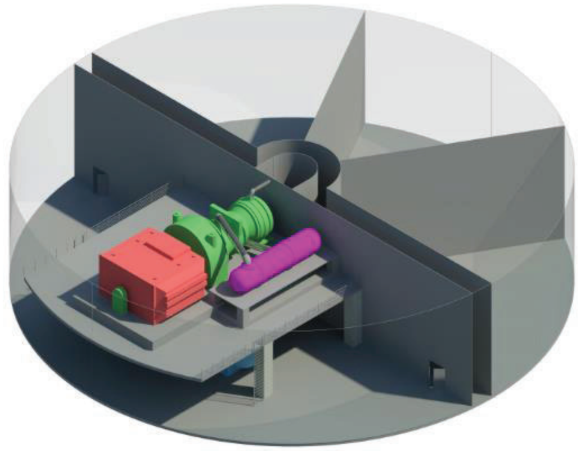

Figure 6. Isometric view of turbine sector, option 10 in Table I.

The main features of the system are shown in the plant layout presented in Fig. 7. Unlike the case of condensing turbine, there is no regenerative steam extractions from any turbines yielding a very simple design, as compared to the opposite extreme of the condensing turbine system. The Aspen Plus analysis for this chapter refers to ‘option 10’ in Table I. The idea is to try to justify the high efficiency loss by maximizing the layout simplicity (thus minimizing costs). The stream leaves the high-pressure turbine stages and flows through a moisture separator, then the vapor stream is reheated (the temperature increase is about 100°C), similarly to the case of the condensing turbine.

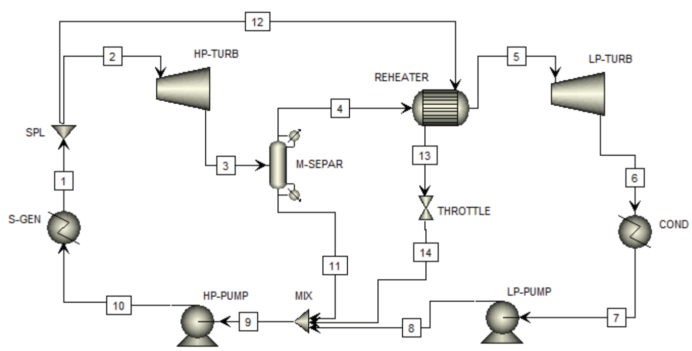

Figure 7. System layout in Aspen Plus V.8.0., option 10 in Table I.

The overall thermal efficiency of the cycle was calculated as:

$$\eta_{th} = \frac{\sum_{i=0}^{I} \dot{m}_i h_i + \dot{Q}}{\dot{Q}_{in}} = \frac{\dot{W}_{turb} - \dot{W}_{pump}}{\dot{Q}_{SG}} = 27.38\ \% \tag{4}$$

where $\dot{W}_{turb} = 250.427\ MW$, $\dot{W}_{pump} = 3.980\ MW$, and $\dot{Q}_{in} = \dot{Q}_{SG} = 900\ MW$. It can be seen that, compared to the condensing turbine design, the backpressure turbine design results in a 84 MW (or 25%) reduction of net power output. Assuming a price of electricity of 80-100 $/MWh and a 90% capacity factor, this power output reduction results in a loss of revenue of $53-67M per year. The backpressure option becomes attractive only if this revenue loss is more than compensated for by a reduction in the capital cost of the BOP, which seems highly unlikely. Therefore, the backpressure turbine option is discarded from further consideration.

3.3. Turbine Missiles

Protection against turbine missiles is a requirement for all nuclear power plants, and especially for the OFNP, where all components are concentrated in a limited space. Plants must show that the risk from turbine missiles is acceptably small, either because design features are provided to prevent damage from a missile strike or because the probability of a strike is sufficiently low. Turbine orientation and placement, shielding, quality assurance in design and fabrication, inspection and testing programs, and overspeed protection systems are the principal means of safeguarding against turbine missiles. Evidence indicates that low-trajectory turbine missile strikes will be concentrated within an area bounded by lines that are inclined at 25 degrees to the turbine (Fig. 8) wheel planes and that pass through the end wheels of the low-pressure stages [10].

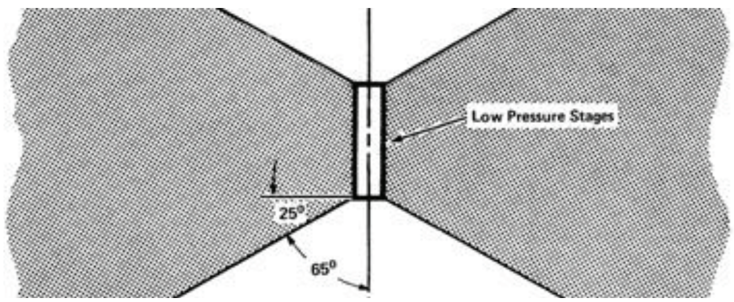

Figure 8. Low-trajectory turbine missile strike zone. Image taken from the U.S. NRC Regulatory Guide RG 1.115 [11].

In the OFNP the turbine cannot be placed in a separate building, sufficiently far from the rest of the plant. Moreover, the orientation of the turbine cannot be adjusted. Thereby proper shielding must be provided to protect all components from the risk of turbine missiles.

4. POWER TRANSMISSION FROM THE OFNP TO THE ON-LAND GRID

4.1. Transmission System

Power is produced at relatively low voltage, between 3 and 30 kV, depending on the size and characteristics of the plant. The voltage is then stepped up by the generator step-up (GSU) transformer to a higher value (115 kV to 765 kV) for the electricity to be transported over long distances.

The offshore alternatives are AC and DC transmissions. The choice of one over the other depends on several factors and varies from situation to situation [12]. AC transmission is more cost effective on short distances (usually less than 80-100 km) and it does not require AC/DC converter stations, which are very large and expensive. On the other hand, AC cables are characterized by a high electrical capacitance. The capacitive charging current becomes significant over long distances, and results in high losses. These trends are illustrated qualitatively in Fig. 9.

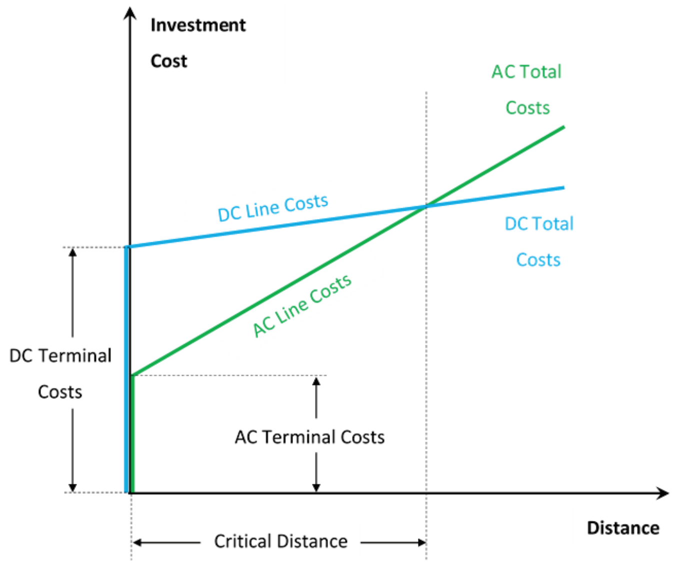

Figure 9. Costs of AC and DC systems as a function of the distance.

The OFNP platform is moored between 10 and 20 km off the seacoast, well below the critical distance for AC transmission mentioned above. Consequently, the OFNP can be connected to the coast through High-Voltage Alternating Current (HVAC) cables. The electrical insulation used for modern HVAC cables consists of an extruded polymer (cross-linked polyethylene, or XLPE) which provides high electrical strength and good mechanical properties at a relatively low weight. These features make it particularly suitable for offshore applications [13]. The next step is to determine what the transmission voltage should be. The line voltage greatly affects the performance of the line and its cost. Equation 5 is an empirical formula commonly used to calculate the optimum transmission voltage [14]:

$$V_{opt}\ [kV] = 5.5 \cdot \sqrt{\frac{D\ [km]}{1.6} + \frac{P\ [kW]}{100}} \tag{5}$$

where D is the cable length, and P is the transmitted power.

Table II. ABB submarine cable characteristics. Bayonne Energy Center project.

Characteristic	Value
Length	3 x 10.4 km submarine XLPE cables 3 x 274 m underground XLPE cables in Brooklyn 3 x 792 m underground XLPE cables in New Jersey
Conductor material	Copper
Conductor diameter	0.036 m
Cable diameter	0.133 m
Conductor specific resistivity ρ	$1.724 \cdot 10^{-8}$ Ωm
Cable weight in water	26 kg/m
Optic fiber	Yes

If one considers a distance of 20 km and a power of 340 MW, the optimum voltage from Eq. 5 is 321.3 kV. Therefore, a standard voltage of 345 kV is selected here. The choice of commercial cables is wide. A good example is the marine cable used for the Bayonne Energy Center project in New York harbor. It is the longest 345 kV AC submarine XLPE cable system currently in use; Table II reports its main characteristics.

Transmission lines have extremely low (but finite) values of resistivity. The following procedure can be used to estimate the fraction of power lost due to resistance. First, the overall resistance is calculated based on the geometrical characteristics of the cable. A correction coefficient α takes into account the fact that ρ decreases with temperature (Equation 6). Finally, the current is calculated and used to determine the power lost (Equation 7).

$$R\left(@\, T_1\right) = R(@T_0) \; - \Delta T \cdot \alpha \tag{6}$$

$$P_{lost} = I^2 \cdot R \tag{7}$$

For a length (L) of 20 km, for a coefficient α equal to $4.29 \cdot 10^{-3}\ \frac{1}{°C}$, and for a water temperature of 10°C, one finds that the power lost due to resistance in the OFNP cable is about 0.3 MW (0.1% of the power transported). An estimated cost of XLPE submarine cables can be calculated with the following formula [15]:

$$C_{AC} = K_1 + K_2 \cdot e^{K_3 \cdot I} \tag{8}$$

where C_{AC} is the cost of the cable in k€/km, the coefficient values (K_1, K_2, K_3) depend on the cable voltage rating and are defined in Table III, and I is the rated current of the cable (Ampere). For $V = 345\ kV$ and $I = 986\ A$, the cost is about 1890 k€/km, which corresponds to \$2.138 Million/km. The total cost of the transmission would be between \$21.380 Million and \$42.760 Millions (the platform is moored between 10 and 20 km off the coast).

Table III. Cost coefficients for XLPE cables (values for 345 kV were extrapolated).

Rated Voltage [kV]	K_1	K_2	$K_3\ [10^{-3}]$
33	45.6	66.1	2.34
45	57.2	67.8	2.33
66	76.3	69.3	2.34
132	219	23.3	3.8
220	353	12.2	4.62
345	570.3	9.3	5.02

4.2. Electrical Substation

To elevate the voltage to 345 kV, the OFNP must have a step-up transformer aboard the platform. In order to ensure the continuity, flexibility of operations and protection of the electric lines and the transformer itself, the platform hosts other components, such as batteries, meters, circuit breakers, disconnecting switches, cable terminations and arrestors. Moreover, depending on the characteristics of the grid, there may be a need to install shunt reactors, which absorb the reactive power that is generated by the charging of AC cables.

Since the space available on the platform is limited and transformers for power generation applications can reach significant dimensions (and cost), the onboard electrical substation must be considered early in the design phase. Table IV shows some characteristics of a generator step-up (GSU) transformer unit close to the OFNP needs [16].

Table IV. 13.8 / 345 kV three phases GSU characteristics.

Characteristic	**Value**
Type	Three phase GSU transformer
Voltage	13.8 / 345 kV
Capability	300 MVA
Price (approximate) *	$ 2.5 Million
Weight (approximate)	185 tons
Dimensions (approximate)	6.4 m x 12.2 m x 8.2 m

* Price is FOB factory. It does not include transportation and other costs. The final price is 25-30% higher.

The primary (input) voltage, the secondary (output) voltage, and the load capacity determine the size of a power transformer. A power plant transformer for power plants is a large, custom-built piece of equipment. Because these components are very expensive and tailored to customers' specifications, they are usually neither interchangeable with each other nor produced in large numbers. According to an industry source, approximately 1.3 transformers are produced for each transformer design [17]. However, for the OFNP significant economy of mass production could be achieved, since the design will be standardized to extent possible.

Oil Immersed Transformers (OIT) are used for the vast majority of applications. Nevertheless, the market offers also Gas Insulated Transformers (GIT), which have a set of interesting features. First, GITs employ SF_6 gas as the insulation and cooling medium, which avoids the need for fire protection equipment, oil collection tanks and pits outside the transformer room. Moreover, since the rise in tank pressure for an internal fault is very small compared with the OIT transformers, the GIT tank will not over pressurize on internal fault [18]. These characteristics have a positive impact on the overall compactness of the system. On the other hand, Gas Insulated Transformers give rise also to several concerns. SF_6 is a potent greenhouse gas, with a global warming potential about 23,900 times that of CO_2 (over a period of 100 years). The only usage of SF_6 not banned in the EU is actually related to high voltage switchgears. Another drawback is the very little experience associated to this technology. For example, there is no IEEE or industry standard practice guidance in North America. Lastly, the cost of a GIT is about two or three times as an equivalent oil-filled transformer (and the long-term costs still have to be fully understood). These considerations lead the authors to believe that the traditional OIT is the best choice for the OFNP project in the near future.

The main cost for substation electrical equipment comes from the MV/HV transformer. For MV/HV transformers from 50 to 800 MVA, a simple expression is provided in [19]:

$$C_{TR,50} = 48.467 \cdot (P_{tr})^{0.7513} \quad (9)$$

where C_{TR} is the cost of the transformer [k$], and P_{tr} is the rated power of transformer [MVA]. If we consider a power of 340 MW for the OFNP, we obtain a cost of about $3.9 M. This estimate refers to transformers for use at 50 Hz. The materials used in the manufacture of the transformer vary depending on the nominal frequency. Thereby, a correction factor can be used for other frequencies.

$$C_{TR} = \left(\frac{0.325 f_r + 0.22 f_r + 0.164 \sqrt[3]{f_r^2}}{0.325 + 0.22 + 0.164} \right) \cdot C_{TR,50} \qquad (10)$$

where f_r is the normalized frequency. According to the equation, the cost of the transformer for use at 60 Hz is about \$3.3 M.

5. CONCLUSIONS

The conceptual design of the balance of plant (BOP) was developed for the OFNP. The following conclusions can be drawn:

- The single condensing turbine option has proven to be the best compromise between efficiency and compactness, assuring high efficiency (36.8%) and power rating (~330 MWe). However, some modifications of the deck ceiling are necessary to accommodate the turbo-generator height.
- The double turbine design also has high efficiency (36.2%) and flexibility but likely a much higher capital cost.
- The design with a backpressure turbine, although very compact, is to be excluded: efficiency and power output drop drastically (to 27.4% and 250 MWe, respectively), which would result in a significant economic penalty.
- High Voltage (345 kV) AC cables represent the best option to transmit power from the platform to the grid.
- Voltage step-up must be performed aboard the OFNP platform. Oil Immersed Transformers (OIT) are currently a more mature option for OFNP than Gas insulated Transformers (GIT), despite being considerably larger.

For the future development of the project, several challenges were identified, including the study of the proper shielding against turbine missiles and the analysis of the effect of ocean wave-induced low frequency oscillations on the turbo-generator shaft, bearing and seal systems.

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