

Powering Small Grids And Islands Using Floating Nuclear Power Plants

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ABSTRACT

The emergence of small modular and micro reactors has brought new possibilities, in general, but perhaps even more so to small power grids and islands that have historically been considered too small to even contemplate using nuclear power. With power output ranging from 5 MWe to 300 MWe, small modular and micro reactors can be adopted to a very large range of usage. In this paper, the possibility of using Floating Nuclear Power Plants (FNPP) is being considered and analysed. These floating nuclear power plants have many similarities with ships, but they deliver power to grids and not to propulsion. Furthermore, being anchored up in one jurisdiction simplifies the nuclear regulatory aspects compared to ships unless it is built in another jurisdiction and is moved around. However, FNPPs share the benefits of being build and decommissioned on a single shipyard as opposed to on-premises, and they resist earthquakes and tsunamis very effectively. Furthermore, being operated by a small electricity grid, or islands, the manning situation is not very different from a ship. For a small grid or an island, recruiting enough people to operate a self-sustained nuclear power plant can be difficult. Hence, by using the same types of reactors that are suitable to those on ships, small grids and islands should have a realistic option. In the NuProShip I project, such reactors are selected after subjecting all available reactor technologies to 37 criteria. However, an analysis of a FNPP for electricity production is not performed. This paper will present such an analysis. The technologies in question are helium gas-cooled reactors, molten-salt reactors and lead-cooled reactors. However, only certain kinds are relevant due to proliferation and security concerns that also can be found in small grids and island. TRISO fuels have therefore been chosen for the helium gas-cooled- and the molten-salt reactors, and uranium nitride for the lead-cooled reactor due to their proliferation resistance. The purpose of this paper is to perform a high-level, conceptual techno-economic analysis of the proposed FNPP using different configurations of reactor technologies and number of reactors ranging from the very smallest of 5 MWe to a double installation of lead-cooled reactor giving in total 110 MWe or higher with more units.

Keywords: *Floater, High Temperature helium Gas-cooled Reactor (HTGR), Molten Salt Reactor (MSR), Liquid lead Fast Reactor (LFR), TRISO.*

1 INTRODUCTION

Small power grids and islands have historically been considered too small to even contemplate using nuclear power. However, the emergence of Small- and Micro Modular Reactors (SMMR) covering the entire range of electric power output from almost zero to 300 MWe may alter this notion, and as early as in 2001 the US Department of Energy [1] issued a report about suitable designs that could be ready over the next decade for remote areas. Such small grids will, however,

have limited personnel pool to draw from, like a ship, and for islands the degree of isolation can also be conceptually similar to ships.

Therefore, using nuclear reactors suitable for nuclear-powered commercial shipping purposes could be a good start, as discussed in Section 2, and it offers a different starting point than suggested by [1]. However, with ships having a higher alternative/opportunity cost (the cost of Heavy Fuel Oil (HFO) or Marine Diesel Oil (MDO)) than power for grids, the economics will be different and perhaps more challenging for Floating Nuclear Power Plants (FNPP) unless the application is deemed particularly valuable for other reasons, such as national security interests and other highly valuable applications.

The economics of the FNPPs must be separated into distinct cases due to the difference in design- and regulatory requirements. The US NRC suggested a very useful distinction of the various types of FNPPs depending on their siting [2]: 1) ‘offshore’, at sites several miles from the shoreline; 2) ‘nearshore’, at sites within one mile of the shoreline; 3) ‘alongshore’, at sites adjacent to the shoreline; and 4) ‘inshore’, at sites which were excavated within the shoreline itself. However, there is an untreated risk associated with the latter two.

Any barge-mounted solution lying in what we can label as the ‘splash zone’ of the ocean may be hit by both earthquakes as well as tsunamis. None of them can be forecasted nor fully prepared for if its origin is close or it travels over deep waters where the speed can reach almost 1000 km/h. As shown in Figure 2, by avoiding the shallowest waters, placing the FNPP at depths of 50 meters or more, the risk is greatly reduced. The waves will basically never approach anything with threatening heights or speed. In fact, Lee et.al. [3] estimate that at 30 meters depth, the waves will reach 12 meters, which is well within design parameters. This author therefore ascertains that placing the FNPP in the splash zone to be an unnecessary risk. Thus, only Offshore- and Nearshore FNPPs offer the benefits of no earthquake risks and no tsunami risks.

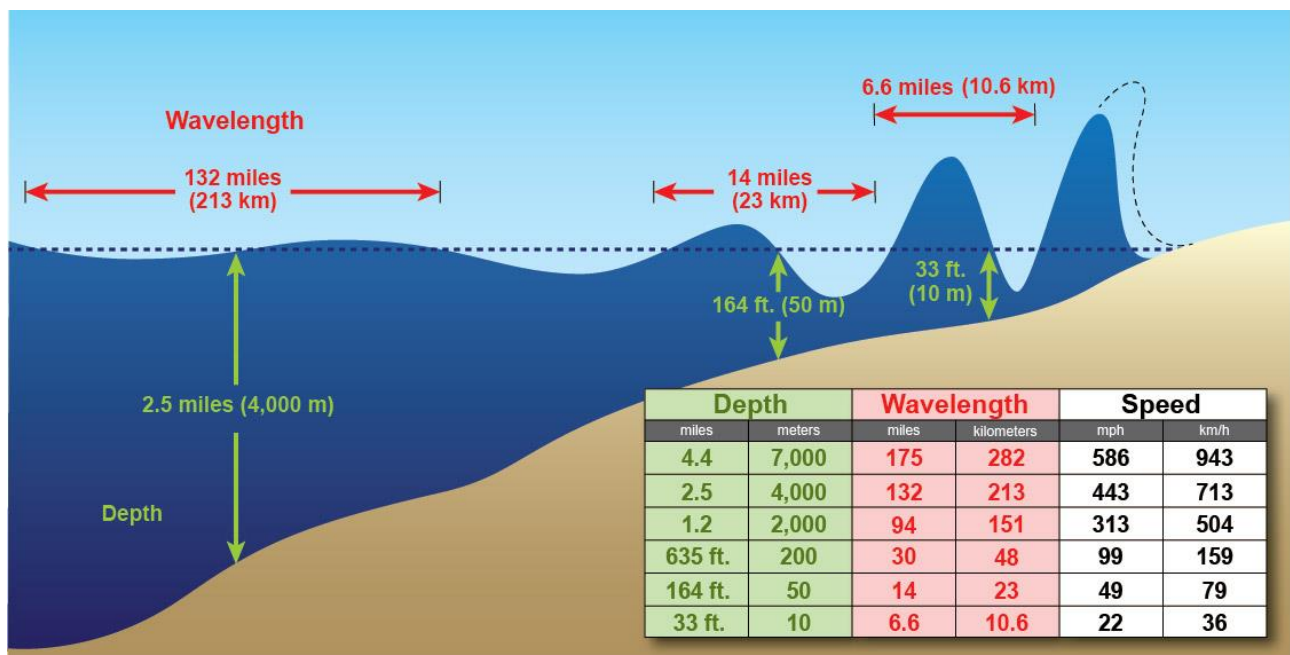


Figure 1: Cross section of a tsunami as its long waves move through the ocean and compress as they approach the coast. Source: [4].

To complicate the matter, the exact costs of the Generation IV reactors proposed in Section 2 are highly uncertain. However, it is certain that FNPPs discussed here require less concrete than for a land-based Nuclear Power Plant (NPP) for construction. Therefore, the best option for this initial paper is to address the FNPP and reactor sizes relatively to a similar installation on land, because the size of the FNPP quickly adds installed effect and costs. Moreover, the tender boat to and from the FNPP with people and equipment adds costs.

Therefore, the following research question is addressed; “at what electric reactor effect will the difference in the capital expenditures (CAPEX) tilt in favour of Offshore FNPPs and Nearshore FNPPs compared to land-based NPPs?” The first step is to identify suitable reactor technologies. This is discussed in Section 2 along with the existing literature on FNPPs. Then, in Section 3, the methods and data are presented followed by the results in Section 4. Conclusions are provided in Section 5.

2 REVIEW OF RELEVANT LITERATURE

There are two strands of literature that are of particular interest to this paper. First, the literature on reactor selection, as discussed in Section 2.1, and the literature on FNPPs, which is discussed thereafter.

The need to review reactor selection processes arises from the political risks of nuclear power. Basically, maritime risk insurers are reluctant to take on insurance objects where there might be a long tail of unresolved cases. The reason is the highly unpredictable outcome of court cases involving radiation risks as demonstrated by nine cases in South Korea [5] or 50 cases in the US [6]. For some, a sunk FNPP can to a much higher degree cause long-term uncertainties about the environmental risks and implicitly human health, than a land-based NPP.

2.1 Selecting nuclear reactors for FNPPs

A FNPP has another risk profile than a land-based NPP as mentioned initially. By defining 37 criteria and subjecting all known SMMR designs by 2023 to them, the NuProShip I / II projects identified three designs that are very promising [7]; 1) a High Temperature helium Gas-cooled Reactor (HTGR), 2) a Molten Salt Reactor (MSR) and a 3) Liquid lead Fast Reactor (LFR) where the former two use TRIStructural-ISotropic (TRISO) fuel whereas the LFR uses uranium nitride. These reactors range from 5 MWe (HTGR) to 55 MWe (LFR). Thus, their size is highly applicable for small grids and islands.

However, these reactors also satisfy criteria that may seem unnecessary for FNPPs. Specifically, criteria related to port entry may seem superfluous. However, FNPPs can still move. Indeed, one of the key concerns is the very mobility of FNPPs which raises new questions, particularly when they move across international borders or operate in international, rather than territorial, waters [8]. Yet, even if we relax such criteria, the end selection will be the same as for ships because:

- 1) Relaxing the port entry criteria would nominally bring back reactors with liquid fuel (all MSRs). The MSRs would be brought back because without port entry, the accounting rules for ports related to proliferation concerns (liquid fuel is not countable) would not apply. Thus, the same proliferation regime as on land-based NPP could apply, i.e., by making sure nothing is brought in/out without inspection.
- 2) The Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR) would no longer had to satisfy the requirement of extremely small emergency planning zones limited to the ship hull because an FNPP will not lie close to another FNPP in a port or next to anything else.

Yet, despite these relaxations of the criteria, the environmental risk criteria associated with the release of radioactive material of a sunken asset remain. MSRs with liquid fuel would release the fuel into the environment as would the uranium oxide in PWRs. TRISO fuel, however, can retain fission products for thousands of years – exactly how many years is still not resolved.

One study indicated the lifetime of the TRISO-coated particles was between 3,100 and 190,000 years [9], but at seawater temperatures (20°C), another study estimated the lifetime to be on average 104,000 years [10]. The pressure of great sea depth may change these numbers, but with even lower temperature and higher pressure the lifetime is also extended. Hence, the net effect is

difficult to assess as of today. Finally, the mass of the TRISO pebbles and pellets would ensure that they sink relatively closely to the FNPP enabling recovery if water depths are manageable. Thus, research so far indicates that TRISO fuel in seawater will have negligible environmentally measurable effects even in the worst case.

Thus, the selection of reactors for commercial nuclear-powered ships, see [7], is sufficiently conservative to represent a viable solution for islands and small power grids. Indeed, it might be argued that it is potentially too conservative. However, with the limited personnel pool of small islands in particular, this author is of the opinion that it is better to start out conservatively and subsequently relax the requirements than to risk incidents and complex regulatory processes, with subsequent increases in costs, delays and erosion of public perception.

2.2 The literature on FNPPs

The first FNPP consisted of a 10 MWe PWR mounted on a converted liberty ship to supply power to the Panama Canal Zone from 1968-1975 [11]. Then, in May 2020, Russia put in operation SMR Akademik Lomonosov which has two KLT-40S reactor units that can generate up to 70 MW of electric energy and 50 Gcal/hr of heat during its normal operation [12], see Figure 2. Thus, FNPPs is clearly an option to consider for both small grids and islands. Its location suggests that Russia has ambitions to enable commercial shipping routes through the North-East passage north of Siberia [13].

A recent study used a cluster of advanced reactors currently under development to provide a power output of 35–70 MWe (which can be reduced to a minimum of 5.25 MWe) with TRISO fuel, corresponding to the highest electrical power demand of four to six large cruise liners in port [14]. It is conceptually similar to Akademik Lomonosov except that it is based on using HTGRs with TRISO and not small PWRs. The concept is alongshore protected by wharfs, as shown in Figure 2.



Figure 2: SMR Akademik Lomonosov in commercial operations in Russia's Far East at Pevek, Chukotka. Source: [12].

Proper Offshore- and Nearshore FNPP has also been thought of before with studies and investigations dating back to at least the mid-1960s [15]. Interestingly, the arguments presented more than 50 years are very similar to today and worth repeating; “The worsening trends in finding suitable land sites along the coast, power plant cost escalation and schedule delays, the growing concern of environmental impact, and a desire for standardization to facilitate the licensing process have all lent impetus to a serious look at offshore siting”. Also, a joint venture of Westinghouse and Tenneco for delivery of a FNPP to Public Service Electric and Gas Company of New Jersey was discussed. The project stranded due to less demand for electricity than anticipated [16].

About 40 years later, Russia, France and South Korea have several initiatives [17]. However, writing 12 years thereafter, this author can conclude that the only example in operation, as shown in Figure 2, is remarkable similar to earlier cases, see [15]. Thus, the level of innovation has been modest, and none address Offshore- and Nearshore FNPPs as discussed here.

In fact, the limited historical cases of FNPPs suggest that they were employed for strategic purposes where cost is a less important criteria than the strategic ones. This study will therefore aim to better understand the competitive parameters where an Offshore- or Nearshore FNPP will outperform a land-based NPP. Regulatory issues are excluded since they are not resolved as of today other than at the part of the oceans outside any Economic Exclusion Zone (EEZ), i.e., the high seas, where FNPPs would be treated as artificial islands under the provisions of the Convention on the Law of the Sea adopted by UNCLOS III [16].

There is nevertheless some recent literature to build on. One of the earliest studies, present a very large Offshore- or Nearshore FNPP dubbed ‘Gravity-Based Structures’ (GBS) FNPP, see Figure 3. Its economic competitiveness is unclear since its sheer size will make shipyard construction difficult. For reference, the two domes are large enough for housing an APR1400. However, the authors show that the total footprint is reduced by 60% compared to the original land-based NPP [3], suggesting that it is also economically more attractive than a land-based NPP. For the purpose of this paper, however, it is far too large, and it will also require a too large and diverse personnel base like-land-based NPPs due to its choice of large PWRs.

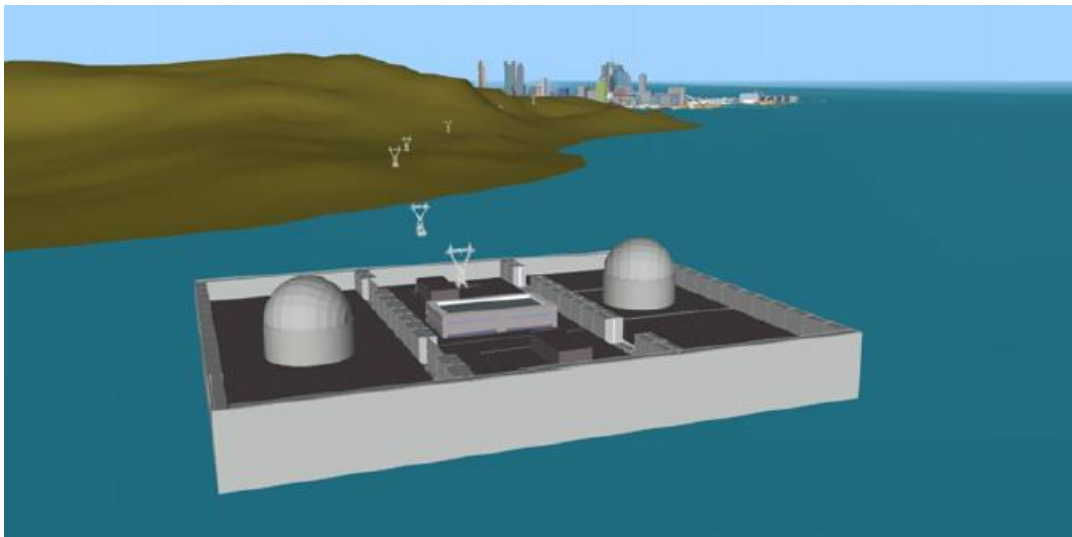


Figure 3: Gravity-Based Structures (GBSs) FNPP. Source: [3].

A much more relevant solution is the existing Sevan platform design [18], see Figure 4, which is a SPAR (Single Point Anchor Reservoir) type platform used in the offshore oil- and gas industry. The effect is 300 MWe, but it requires substantial draft – 48.5 meters. It has a steel mass of about 14,100 tonnes. Also, it is based on PWRs, but that can obviously be changed to the reactor technologies discussed here.

The safety aspect of the design is very good. The plant’s thermal-hydraulic responses to two postulated accidents, i.e., loss-of-coolant accident (LOCA) and station blackout (SBO), are studied in three scenarios [19]: 1) a design-basis 100-yr storm, 2) a bounding scenario in which the platform is assumed to pitch and roll with an amplitude of 20 degrees, and 3) a bounding scenario in which the platform experiences a static tilt of 30 degrees. The RELAP5 analysis shows that the safety margins of OFNP-300 are not challenged in the aforementioned three postulated scenarios.

There are, however, other floating structure designs used in the offshore oil and gas industry that are worth considering, with more shallow draft than the Sevan platform while maintaining stability and sufficient deadweight to handle reactors and enclosures with a good margin. This is discussed in Section 3.2.

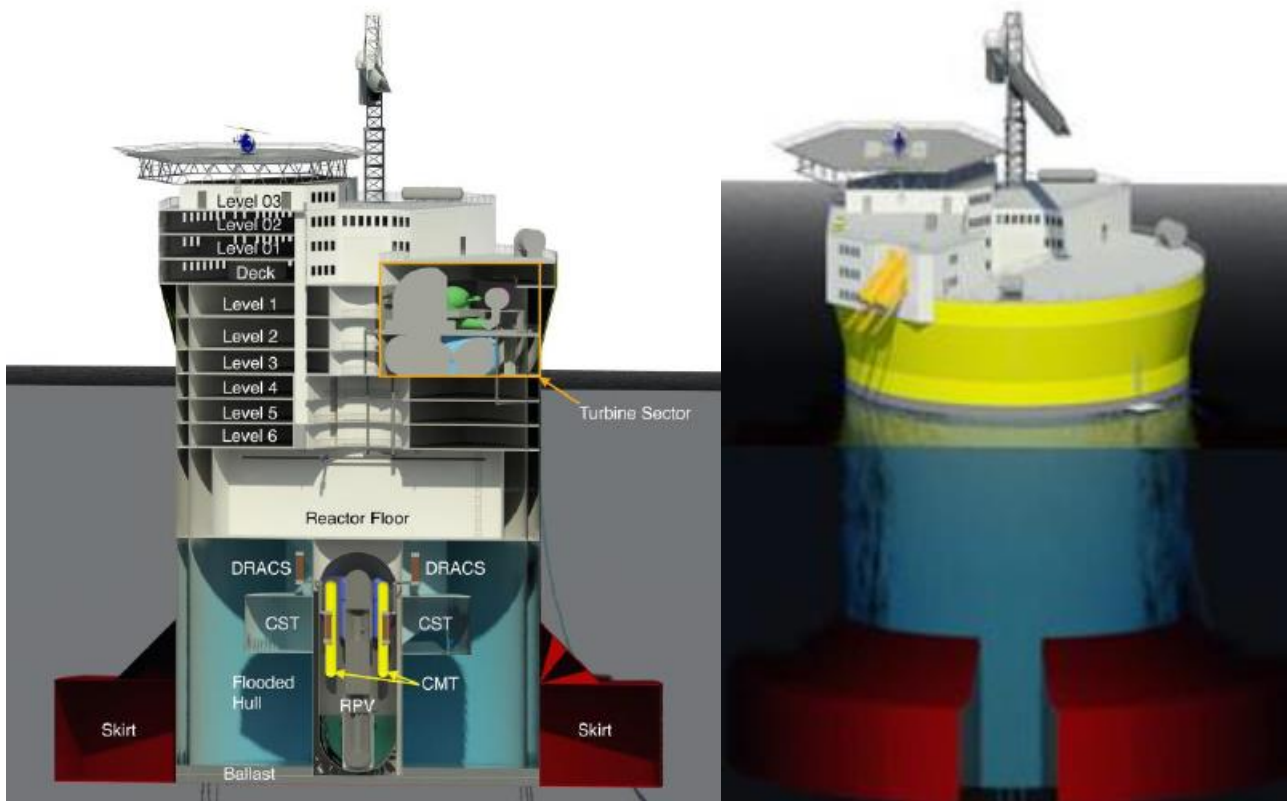


Figure 4: Isometric views of OFNP 300. Source: [18].

3 METHODS AND DATA

Since FNPPs also have 1) upward limits concerning size, because they are built in shipyards, and 2) they must satisfy safety at sea rules and regulations, the best approach is to evaluate floater designs that are already tested and approved. The benefit is that also construction costs can be known. To represent a viable alternative compared to the Sevan design, it must have significantly smaller draft. In the next three sections, FNPP concepts are discussed along with the land-based NPP reference case. All relevant data are provided.

3.1 Land-based NPP reference case using PWR

As a reference case, its main function is to provide a comparison. One recent and useful literature review/study investigates the Overnight Construction Costs (OCC) of various NPP technologies and provide a relative cost breakdown as shown in Table 1. The OCC excludes financing charges, and it is the dominant cost both of the life time costs for nuclear power, and the cost component that varies most over time and between countries [20].

Most of the cost items in Table 1 will not notably change from land-based NPPs to FNPPs. Therefore, we must identify those items that actually are impacted. Item 21 – Structures – will obviously be a key item that will change. Item 25 – Heat rejection system – will also change but it is currently very difficult to estimate to what a degree. However, since a FNPP is literally situated on top of the heat sink, it is assumed that Item 25 will be reduced by 50%. Also note that the numbers are different from reactor technology to reactor technology. For example, structures constitute a far smaller share of the total overnight costs of a HGTR than for a PWR.

The study [21] also identified the direct costs from the literature. For this study, it suffices to include the Capital Expenditure (CAPEX) part, which ranges from 4000 USD/kWe to 7000

USD/kWe with a most likely estimate of 6000 USD/kWe. Using the most likely estimate, a 100 MWe NPP will have structural costs and half the heat rejection costs equalling 57.2 MUSD for a PWR. Similarly, the CAPEX will become 17.8 MUSD for a HTGR and 59.8 MUSD for an MSR. These two estimates, however, are highly uncertain due to the lack of construction experience. Therefore, the reference case is a PWR.

Note that the assumption that CAPEX is directly proportional to power level is probably questionable at least for broader ranges of reactors across different reactor types. However, it provides an approximation for an early study like this.

Table 1 – Overnight construction cost breakdown for various reactor technologies. Note that the Sodium-cooled Fast Reactor (SFR) included in Table 1 is not a part of this study but included here for the sake of completeness. Source: [21].

Overnight costs		PWR	SFR	HTGR	MSR
10	Pre-construction costs	1,99 %	4,63 %	1,01 %	2,31 %
20	Direct costs	33,56 %	43,24 %	33,87 %	33,31 %
21	Structures	8,75 %	9,63 %	4,77 %	8,10 %
22	Reactor equipment	10,58 %	20,90 %	12,44 %	12,26 %
23	Energy conversion system	7,42 %	3,39 %	7,68 %	6,89 %
24	Electrical equipment	3,32 %	4,85 %	6,83 %	3,84 %
25	Heat rejection system	1,56 %	2,89 %	2,15 %	0,98 %
26	Miscellaneous equipment	1,94 %	1,58 %	0,00 %	1,23 %
30	Indirect costs	37,38 %	29,96 %	37,73 %	37,10 %
40	Owner costs	10,64 %	8,53 %	10,74 %	10,56 %
50	Supplementary costs	1,08 %	0,92 %	0,81 %	1,23 %
60	Financial costs	15,35 %	12,73 %	15,84 %	15,48 %
Annualized Costs					
70	Operating staff costs	95,98 %	58,14 %	55,62 %	98,18 %
80	Fuel costs	4,02 %	41,86 %	44,38 %	1,82 %

3.2 The Offshore- and Nearshore FNPP case

Excellent seakeeping properties are required for Offshore and Nearshore FNPPs, otherwise the FNPP could become unsafe for its crew as well as operations in general. One of the designs that satisfy such requirements is shown in Figure 5. It is primarily designed for offshore usage for the oil and gas industry, and laboratory tests gave excellent results.

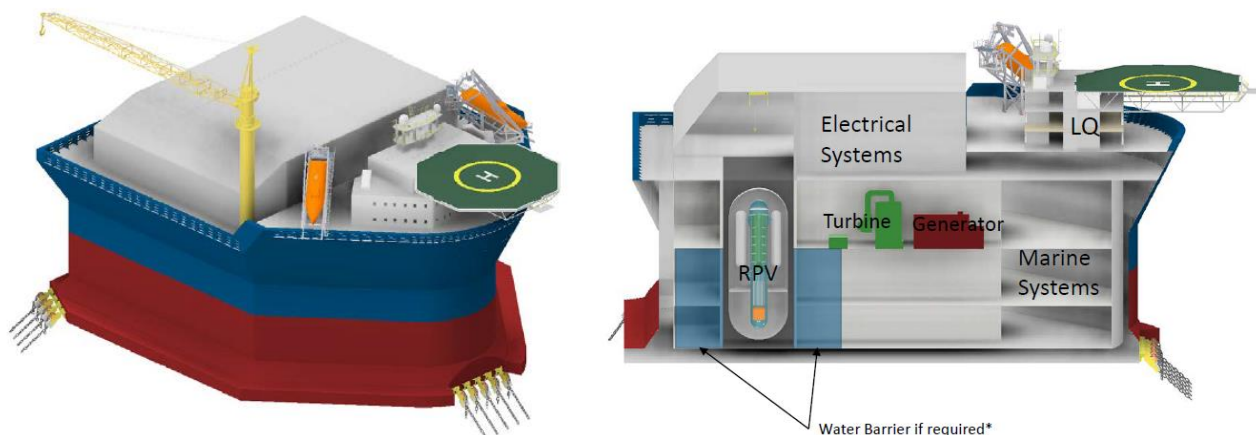


Figure 5: FNPP design for Offshore and Nearshore applications. The water barrier can be arranged for extra shielding. Used with kind permissions from Cefront Technology AS.

The main data for the FNPP is shown in Table 2. With unit cost of 5 kUSD/tonne including all marine systems, the deterministic construction costs are shown at the bottom. The unit cost is based on similar projects that Cefront Technology AS has been involved in, built in China, with a contingency up to 15%. The uncertainty of the unit cost is substantial, so the construction cost is modelled as a symmetrical, triangular uncertainty distribution of 5 ± 1 kUSD/tonne. The contingency is modelled as a uniform uncertainty distribution ranging from 0% to 15%. The tender boat must also be added. A CAPEX of 2 MUSD and an Operating Expenditures (OPEX) of 1 MUSD/year are assumed.

To assess the impact on electricity costs, the Net Present Value (NPV) of the difference between the land-based NPP and the Offshore- or Nearshore FNPP is estimated. The lifespan is assumed to be 30 years, and the Weighted Average Cost of Capital (WACC) for long-term assets is assumed to be 4.5%. The WACC is based on using 7.9% as return on equity, which is historically high [22], 4% interest rate on debt, 23% corporate tax rate¹ and a 30%/70% equity/debt ratio [23].

Table 2: Main data for the open sea FNPPs. Source: Cefront Technology AS.

Model	CF100	CF150	CF200	CF300	CF500
Length, waterline [m]	48.0	55.0	60.4	69.2	82.0
Width, waterline [m]	37.4	43.0	47.2	54.0	64.0
Depth, main deck [m]	18.7	22.0	23.6	27.0	32.0
Draft [m]	8.8	9.0	11.1	12.7-18.6	15.0-22.0
Displacement [tonnes]	14,802	20,203	29,603	44,402-63,663	74,000-106,100
Suggested reactor size [MWe]	50	100	200	400	600
Indicative hull mass [tonnes]	2,720	4,080	5,440	8,160	13,600
Unit CAPEX [MUSD]	35	43	51	66	98

The remaining uncertainties are substantial, but handling a large variety of uncertainty is straightforward with today's computers by using Monte Carlo simulations [24]. The key uncertainties are modelled as shown in Figure 6. Concerning the WACC, it has some degrees of uncertainties mostly related to interest on debt. It is assumed that it can be modelled as a triangular uncertainty distribution with $4.5\pm 0.5\%$ as shown in Figure 6.

Note that using semi-submersibles, commonly used in the oil and gas industry for drilling operations and the like, can be envisioned but the author has not found any such studies. Due to their more open design and less buoyancy than those discussed here, it will require more details to assess their applicability. Interestingly, a patent was been filed for it [25], but it was later abandoned and it actually displayed a SPAR.

3.3 The Alongshore FNPP case

Another approach is to use an Alongshore FNPP provided that the earthquake risks and tsunami risks can be mitigated through detailed seismic analyses and tsunami traveling times to allow the Alongshore FNPP to be located at a safe location concerning earthquakes and moored so that enough time is secured to move it to deeper waters in the case of a pending tsunami. This allows for a much cheaper FNPP and the elimination of a tender boat.

Such an Alongshore FNPP concept is shown in Figure 7. This is essentially similar to the SMR Akademik Lomonosov in Figure 2, except a more durable barge solution is used. The concrete has a 50-year lifespan licensed without any need for maintenance using the same type of concrete that is used for aquaculture rafts in Norway. The cost is about 8 MUSD without the reactor units, turbines and other power production related equipment.

The challenge with this solution is that it cannot host large reactors due to current construction limitations. However, there is space for small reactors such as 2 HTGR at 5 MWe each.

¹ The average OECD corporate tax rate is 23.3% in 2020, calculated with data accessed 2021-01-27 from https://stats.oecd.org/Index.aspx?DataSetCode=TABLE_III

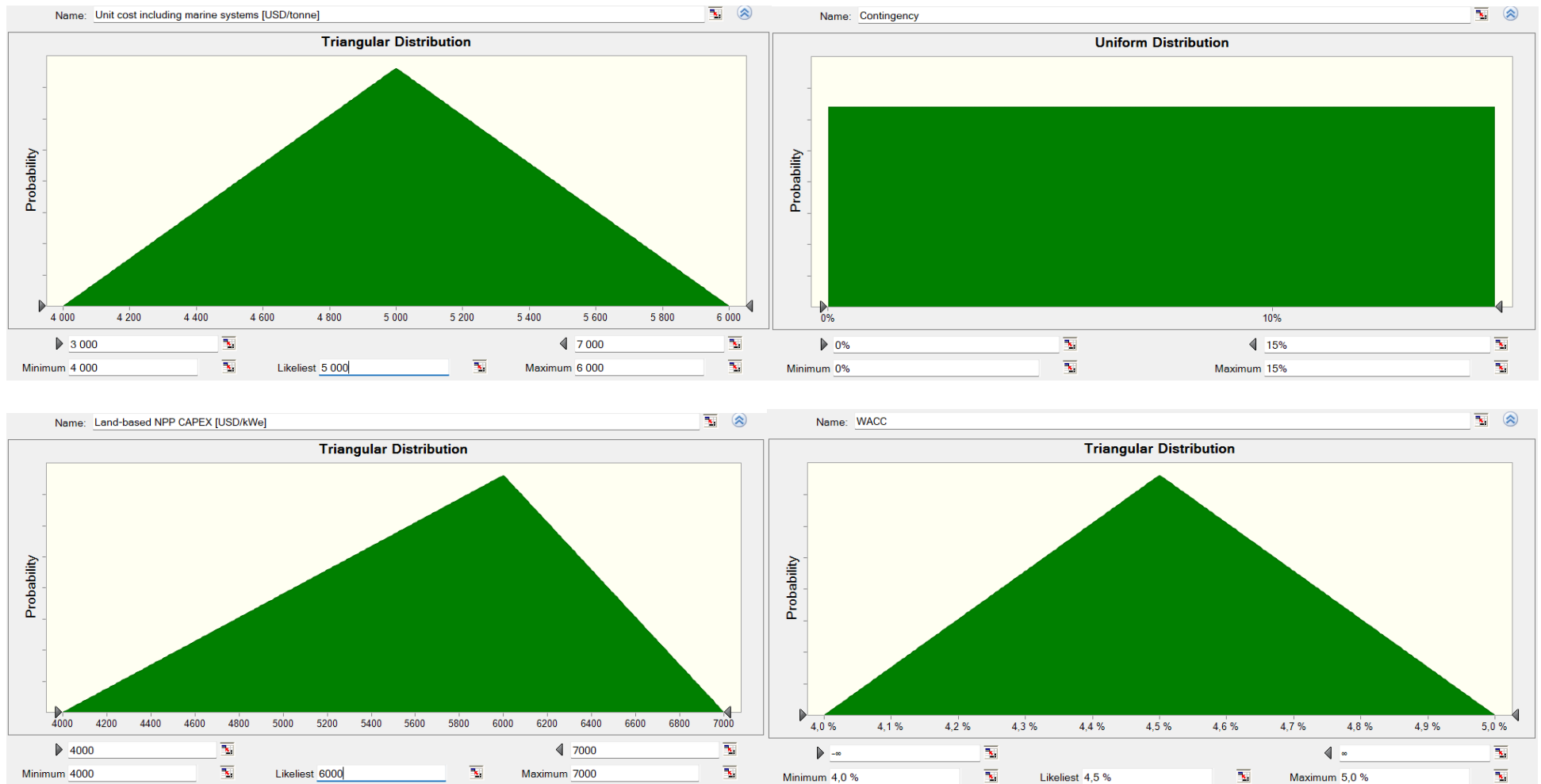


Figure 6: Uncertainty modeling of the key parameters that are uncertain.



Figure 7: Alongshore FNPP developed for test reactor at Norwegian University of Science and Technology in Norway and cooperation with Ulstein Betongindustri AS.

4 RESULTS

The results of the two concepts earlier are discussed in the two subsequent sections.

4.1 Results for Offshore- and Nearshore FNPPs

The deterministic results are shown in Table 3 and Figure 8. Clearly, a very small FNPP are more costly than a land-based NPP. However, with larger FNPPs, and larger power production, the economics tilt in favour of a FNPP. This analysis ignores the fact that FNPPs have a different risk profile compared to land-based NPPs as mentioned earlier, or the benefits addressed in the literature as mentioned earlier. Also, the impact of being built in a shipyard and decommissioned in a shipyard is excluded. The analysis is therefore very conservative concerning the FNPP.

Given the uncertainties in Figure 6, a Monte Carlo simulation is run. The number of trials is 10,000 to minimize randomness in the results caused by the numerical nature of Monte Carlo simulations. The result is shown as an overlay chart for simplicity, in Figure 9. Clearly, the smaller FNPPs are more capital intensive than the land-based NPPs per installed effect. The reason is that

FNPPs need size for favourable motions under all design conditions, and they become a little too large for the smallest nuclear power plants.

Table 3 – Result summary with CAPEX for different sized land-based NPPs and FNPPs and their annual power production [GWh].

Unit size [MWe]	Land-based NPP CAPEX [MUSD]	FNPP CAPEX [MUSD]	FNPP OPEX [MUSD]	Savings [MUSD]	Production [GWh]
50	28.6	37	1	-9.4	394
100	57.2	45	1	11.3	788
200	114.4	45	1	68.5	1,577
400	228.7	98	1	130.1	3,942
600	343.1	98	1	244.5	4,730

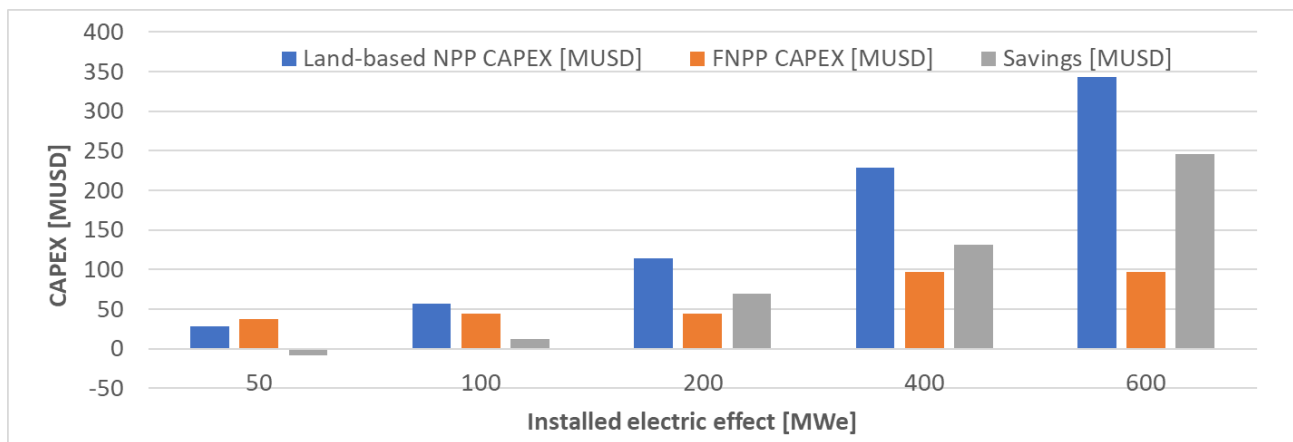


Figure 8: CAPEX for different sized land-based NPPs and FNPPs and their annual power production [GWh].

However, to incorporate the entire economic impact, the effect of time and OPEX for the tender boat must be included using 3% inflation. To do this, the NPV over the lifespan is calculated. To account for the alternative costs, the WACC is used to discount the net cashflow for every year, and the results are shown in Figure 10. Clearly, an Offshore- and Nearshore FNPP must have an installed capacity of at least 200 MWe to be economically worthwhile compared to a land-based NPP given the conservative assumptions. The corresponding annual power output is 1500 GWh.

The average dwelling in Croatia consumed 4,500 kWh in 2023 [26]. Hence, a 200 MWe installation would satisfy the annual power consumption of 350,000 dwellings, or more than five times the size of Split (60,000 households), see [27], which is the largest coastal city in Croatia. Thus, FNPPs can easily become too large even for relatively large cities.

Therefore, the Offshore- and Nearshore FNPP cannot be based on the economics of providing power to dwellings alone unless the current cost is relatively high. Colocation with industrial sites would therefore be beneficial. With the current growth trajectories of Artificial Intelligence, the surplus power might make a location attractive. An alternative is, of course, to accept the higher CAPEX of a smaller FNPP, but that will be a political decision.

Finally, the impact on the cost of electricity should be assessed. The average Levelized Cost of Energy (LCOE) can be estimated by using the NPV and assign it to the power production over the lifespan. The LCOE is the average price of power over a defined lifespan that would balance the discounted life-cycle costs for a source of power [28], and it is the most frequently used metric for comparing energy sources worldwide [29]. The LCOE has a number of shortcomings for intermittent power sources, but for dispatchable power sources – such as nuclear power – it works well [28]. As shown in Figure 11, the impact on the LCOE is small.

Therefore, the rationale of a FNPP versus a land-based NPP is not one primarily based on the cost of power in this conservative study as long as the CAPEX requirements can be met financially.

Hence, an economic argument must be based on the total CAPEX compared to the power demand and supply adjusted for alternative costs.

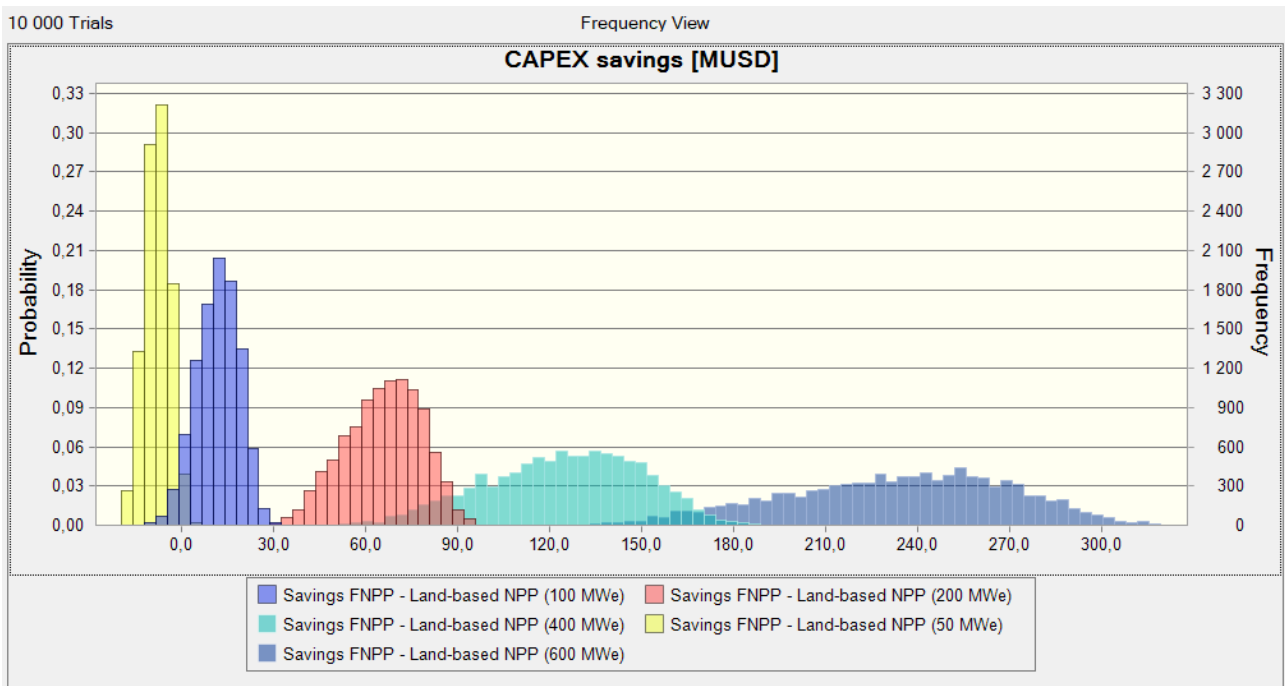


Figure 9: Overlay chart of Savings in CAPEX for an Offshore- and Nearshore FNPP compared to a land-based NPP of equal electric effect.

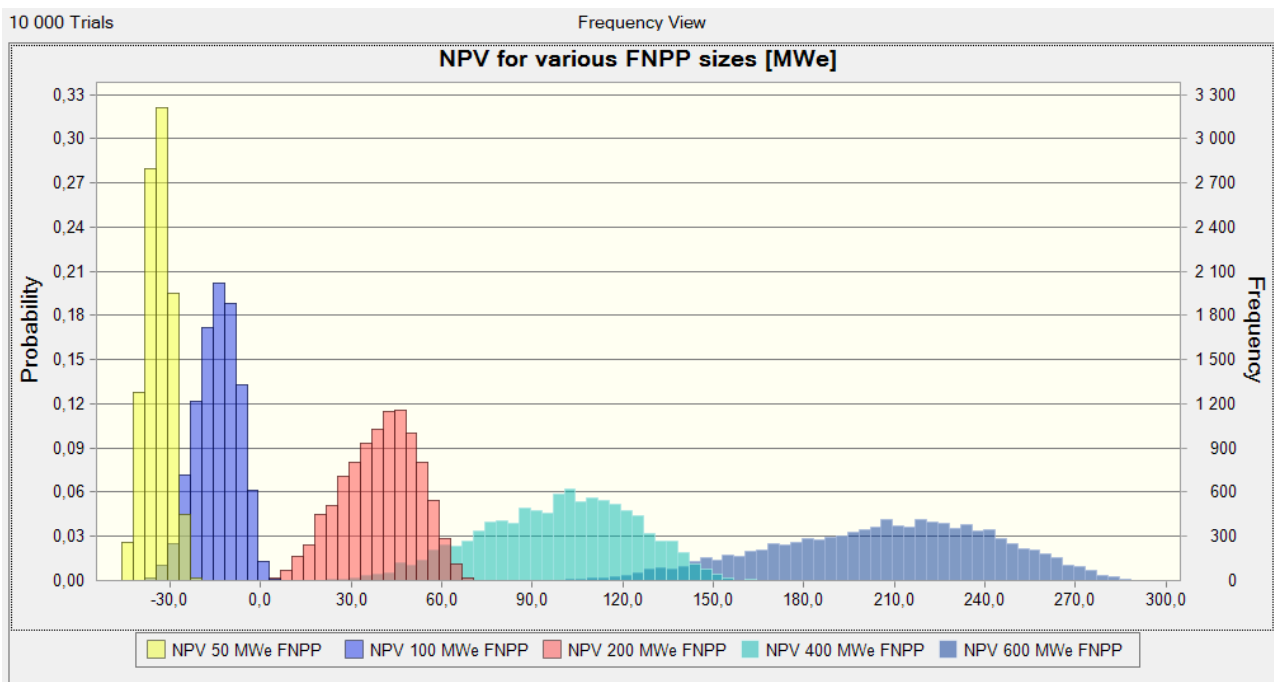


Figure 10: NPV for the various Offshore- and Nearshore FNPP alternatives.

To understand the details better, a sensitivity chart for the NPV value closest to 0 MUSD (the breakeven point) is presented in Figure 12. The most important parameter is the CAPEX of the NPP itself regardless of whether it floats or sits on land. Then, the next two most important parameters are the two FNPP parameters (unit cost and construction contingency) in this simple model. The cost of capital (WACC) is remarkably uninteresting.

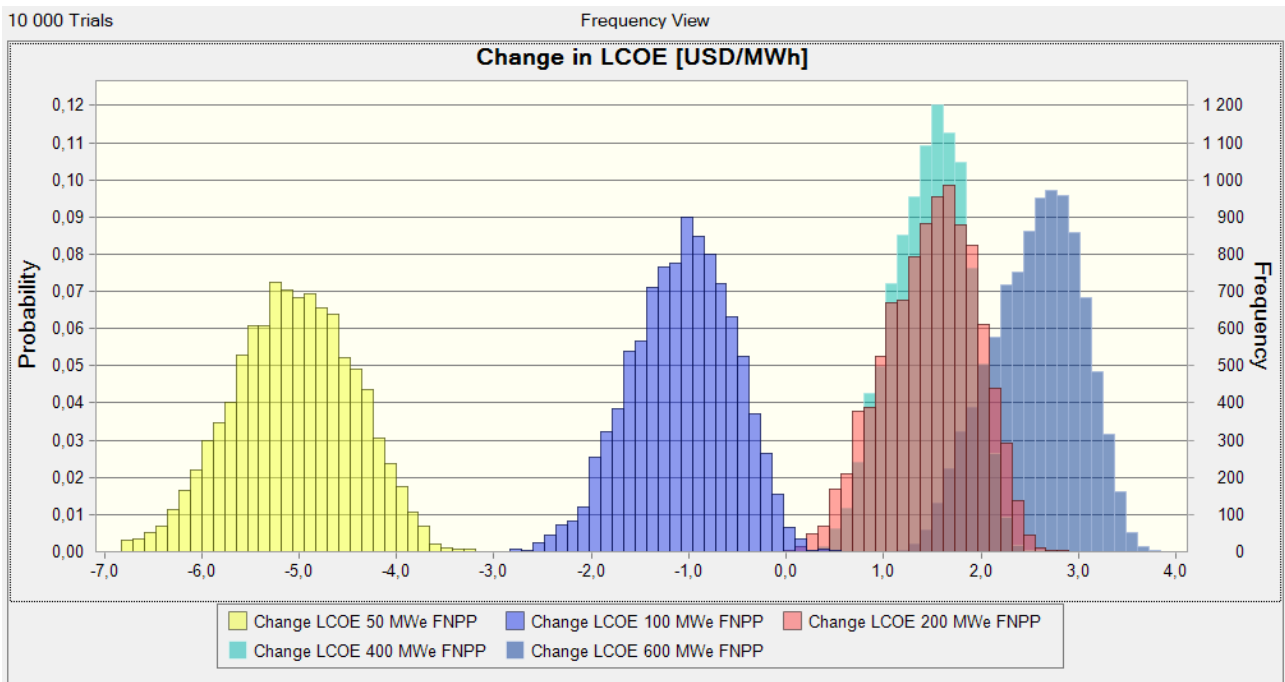


Figure 11: The change in discounted cost of electricity [USD/MWh].

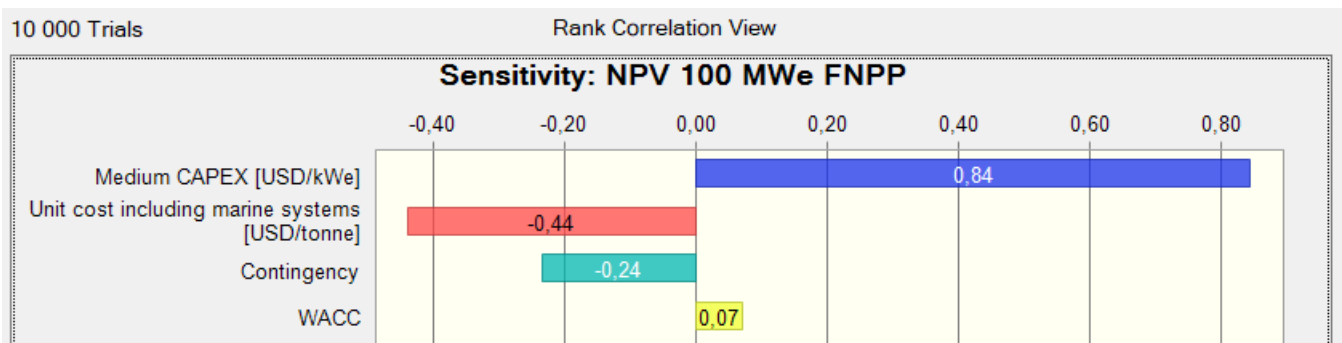


Figure 12: Sensitivity cart for the NPV of the 100 MWe Offshore- and Nearshore FNPP.

These results may seem inconsequential. However, none of the shipyard effects are included, the savings of land area costs, the growing concern of environmental impact, the benefits of standardization and more. Hence, a more detailed study with a concrete case is warranted so that the alternatives can be specified in detail. It is likely that these details will ultimately determine the economic outcome. For example, by building two reactors, and not one, there is a cost saving of 15% – 20% per unit for land-based NPPs [21].

We should also keep in mind that the cost of power for small grids and islands is normally much higher than in large grids due to the lack of scale. Indeed, for the 15 million Europeans living on an island, energy can be extremely expensive – bills are three to four times higher than on the mainland [30]. Therefore, identifying current costs is important to correctly understand the alternative costs of a FNPP, to ultimately determine whether or not a FNPP makes economic sense.

4.2 Results for Alongshore FNPP

The small Alongshore FNPP is difficult to compare to the land-based NPP simply because the 5 MWe HGTR is much smaller than PWRs. However, by using the data in Table 2, we can provide an estimate. The structural costs and half the energy conversion costs will amount to 5 MUSD whereas the Alongshore FNPP will cost 8 MUSD.

Hence, again the FNPP is a more expensive option in this highly conservative case. A small Alongshore FNPP like this will generate 79 GWh/year, or about a third of the households in the city of Split. Its size, however, is highly advantageous because it is very small. Therefore, when all is included, the 3 MUSD difference is probably less than the monetary value of the advantages that are not included in the model. Again, a more detailed analysis from a real-world case will be necessary to determine the actual economic performance.

5 CONCLUSION

This study started by identifying FNPP designs that can be used offshore and nearshore with the objective of keeping the NPP floating outside the reach of any earthquake risks or tsunami risks. With that distance from the shoreline, it resembles a ship, which is why the selection results of a project on nuclear propulsion were chosen. Furthermore, the benefits on using TRISO fuel for ships is equally valid for an Offshore- and Nearshore FNPP because the FNPP can sink – potentially to waters too deep for salvaging.

The study was further delimited by focusing solely on the savings of absent structural elements and some of the heat rejection system of land-based NPPs and then translate these savings into potential FNPP sizes and reactor electric effects. The results clearly show that FNPPs can be as economically viable as land-based NPPs, which is a key finding in itself. Moreover, there are many upsides that are not included. Hence, most likely are FNPPs – even relatively small ones – an economically viable platform for power production for islands and small power grids – particularly as power for such grids is frequently much more expensive than for the mainland.

Much more details and specificity, than offered by this conceptual study, are necessary to ultimately assess whether a FNPP will a viable solution. With sufficient specificity, the sizes can be correct, the regulatory issues can be addressed, the potential for cost savings for the FNPP construction can be identified and, the current costs of providing power to the small grid or the island can serve as a reference point.

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