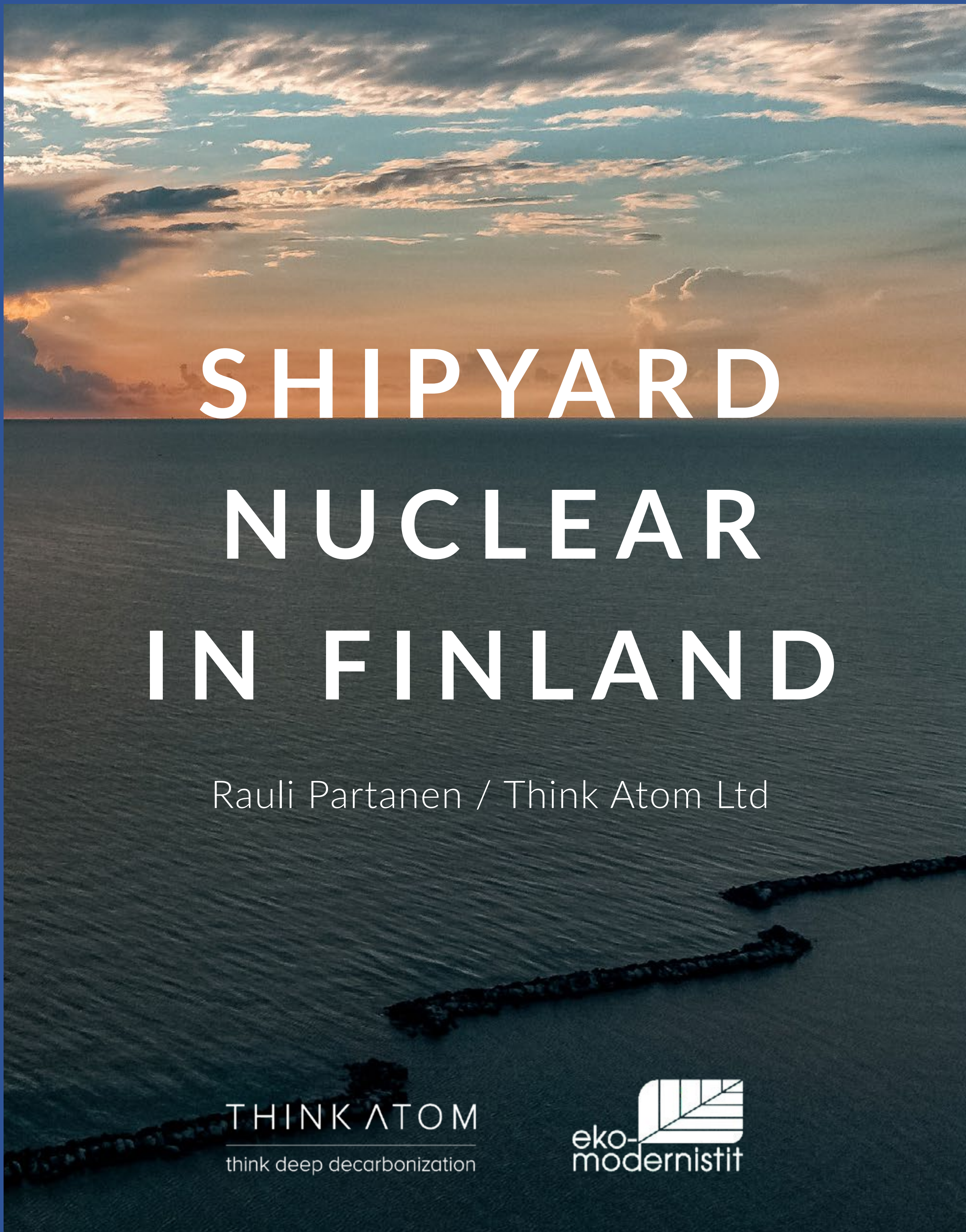


SHIPYARD NUCLEAR IN FINLAND

Rauli Partanen / Think Atom Ltd

THINK ATOM
think deep decarbonization

eko-modernistit

Shipyard Nuclear in Finland

This study was commissioned by The Ecomodernist Society of Finland.
The study was carried out by Think Atom Ltd.
Author: Rauli Partanen

https://ekomodernismi.fi/ | https://thinkatom.net/

eko-modernistit

THINK ATOM
think deep decarbonization

Table of Content

Key Findings

Finland is uniquely positioned to kickstart a new industrial sector of building and operating floating nuclear power plants at its shipyards. Effective design and manufacturing at shipyards can significantly reduce the cost of reliable low-carbon energy production while offering a tremendous opportunity for exports. Finland has many necessary pieces in place, giving us an advantage over other western countries. These pieces include high quality expertise in the broader nuclear industry and shipyard manufacturing, as well as high public and political acceptance for climate mitigation and nuclear energy.

Finnish Shipyards

The three biggest Finnish shipyards could produce 1-4 medium-sized floating NPPs each year. **Using roughly half of the capacity available today, and depending on the design, 1-2 GWe of capacity could be built per year** from the three larger shipyards at Turku, Helsinki, and Rauma. These could be supported by Pori Offshore Construction -shipyard, which has many necessary licenses and certificates for nuclear-grade manufacturing. This rate would equal roughly one EPR sized reactor such as Olkiluoto 3 (at 1.6 GWe) commissioned every year – precisely the step change we need to decarbonize our energy systems effectively

As floating nuclear power plants (FNPPs) can be towed to any location with a waterway and siting is uniquely flexible, the project timelines can be much shorter and the export market global. E-fuels produced in these vessels can also be relatively easily transported for long distances, expanding the market.

The Cost Reduction Opportunity

Several reactor developers and vendors are designing or planning to develop their reactors to be sited on floating barges. The key advantages are cost reductions in manufacturing and site preparations, flexibility in locating the plants, and rapid production scaling due to existing facilities and supply chains. **The cost-reduction potential in shipyard manufacturing is very significant, with CAPEX reductions of 50% within reach compared to on-site construction and 75% compared to recent FOAK projects in Europe and the US.**

This cost reduction translates to CAPEX of around 2,500 €/kWe, which can go even lower with advanced designs and mass production. A levelized cost of electricity (LCOE) below 40 €/MWh should be achievable. If heat is also sold (CHP), the cost is likely lower.

The size and capacity of the vessel play a significant role: A 300 MWe vessel might cost half compared to a 1,200 MWe vessel, effectively doubling the specific cost per MWe for the smaller ship. This difference would likely get smaller with mass production, as the benefits of serial production would decrease manufacturing and licensing costs for smaller vessels.

We can produce carbon-neutral hydrogen at a cost below 2€/kg, ammonia below 300 €/ton, and jet fuel below 90€/barrel of oil equivalent. All are reasonably competitive compared to fossil counterparts and significantly lower than achievable with wind or solar in the near future, not to mention the costs coming from increased storage needs due to unreliable production.

Using vehicles like Mankala-model and securing government support can decrease the cost of financing, further lowering the levelized cost, especially for the FOAK. Advanced nuclear technologies such as molten salt reactors can significantly reduce the costs.

The Markets

Globally, electrification will likely proceed at an accelerating rate. But still, we will need easily one billion tons (preferably much more) of clean hydrogen and e-fuels by mid-century to make a significant dent in the projected global fuels consumption. **We will need 1.5 times the electricity (~40 PWh) the world currently consumes (~27 PWh).**

Europe is in an escalating energy crisis. The combination of nuclear and coal closures and the addition of wind and solar has led to an increasing reliance on mostly imported natural gas. The supply of that gas, of which 40% (~1,500 TWh/year) is coming from Russia, which just invaded Ukraine, has been questioned. **There will be a growing demand for reliable electricity, hydrogen, and e-fuels produced at hundreds of gigawatts.** The evolving situation has led to a rapid re-evaluation of the wisdom of leaving nuclear largely out of European energy policy, and support is rising.

Finland has a growing demand for clean capacity. It wants to decrease reliance on imports (helped by Olkiluoto 3 starting), retire CHP-production (both coal and natural gas), and perhaps some of the first generation of nuclear power plants turning 70 years mid-century. **Just replacing lost and retiring capacity and imports will mean demand for 40-60 TWh of new production – 5-7 GWe of constantly running capacity such as nuclear.** We can meet some of this demand with further long-term operations at the older nuclear reactors in Olkiluoto and Loviisa beyond mid-century.

Depending on ambition, Finnish transportation and industry (metal and chemical) will also require 60 to 100 TWh of clean electricity to decarbonize. **EVs will use 5-10 TWh (~1 GWe), the metal industry around 10 TWh (1+ GWe), and the chemical industry between 40 to 80 TWh (5 – 10 GWe).**

There is a significant opportunity also in the forest industry. Even with current processes, we could capture the bio-based CO_2 from pulp mills and use it as feedstock to make synthetic e-fuels. This will need a significant amount of clean and low-cost hydrogen, which takes electricity. **The CO_2 supply from our pulp mills is substantial and means there is demand for up to 200 TWh (25 GWe) worth of electricity production for making the necessary hydrogen.**

Regulations, Legislation, and Public Acceptance

According to IAEA, sufficient regulations, legislation, and practices exist for floating nuclear power plant pilot projects. Indeed, these projects would offer valuable practical insight as case studies on the myriad of topics that will emerge. In the Finnish context, the current prescriptive regulations can be a big challenge, but these are under review. A lot depends on the details. For example, what kind of reactor technology is used, would the site be at a harbor or at sea, what would be the configuration and end-product of the vessel (electricity or e-fuels) and so forth.

Given that floating nuclear power plants have not been built, operated nor regulated in Finland, there is a lot to do – especially for the first one. The design needs to be licensed, as does the site and operator. After this has been done once, the next "copy", especially at the same site, should be much lighter to license. It would be prudent for the government to share some of the costs for the first-of-a-kind units' licensing costs if it is interested in kickstarting a potentially very significant – both economically and from climate mitigation perspective – new export industry in Finland. The cost/benefit of such an investment should be worth it.

Nuclear enjoys the highest public acceptance in recent history, and many parties and politicians have also shifted to a more positive position, although especially Russian technology for new projects lost its acceptance due to Russia invading Ukraine. Finnish energy industry sees small nuclear reactors (SMRs) as essential for reaching the government's carbon neutrality goal by 2035[1]. Yet at least some key ministry officials and civil servants seem to think there is no urgency, because there are no commercial projects proposed.

It is quite likely that lack of projects is due to the regulatory and legislative environment not being conductive for investing in new SMR-type projects. Therefore, this "lack of projects" is a poor excuse to not reform legislation and regulation rapidly. On the contrary, as we know, and as our energy industry has communicated, these types of technologies are direly needed to decarbonize energy. Therefore, the lack of projects is a clear sign that the bottleneck is somewhere else, and lack of regulation and legislation certainty is a likely candidate.

1 https://energia.fi/files/6320/ET_SMR-positiopaperi_092021.pdf (Finnish)

Lyhennelmä ja avainlöydökset

Avainlöydökset

Suomi on erinomaisessa asemassa luodakseen kokonaan uuden teollisuudenalan, joka rakentaa kelluvia ydinvoimalauttoja suomalaisilla telakoilla ja operoi niitä niin Suomen aluevesillä kuin jatkossa kenties muidenkin maiden rannikoilla. Kustannustehokas suunnittelu ja sarjavalmistus telkoilla voivat laskea luotettavan ja puhtaan energiantuotannon pääomakustannusta erittäin merkittävästi ja tarjota valtavan vientimarkkinan erilaisille tuotteille ja palveluille.

Suomella on pieneksi maaksi poikkeuksellisen monta tarvittavaa osasta hallussaan. Näitä ovat esimerkiksi korkeatasoinen ja osaava ydinvoimateollisuus, osaavat ja kyvykkäät telakat ja korkea yleinen sekä poliittinen hyväksyttävyys niin ilmastonmuutoksen hillinnälle kuin ydinenergiallekin.

Suomalainen telakkateollisuus

Suomen kolme suurinta telakkaa kykenisivät valmistamaan 1–4 keskikokoista kelluvaa ydinvoimalaa vuodessa, kukin. **Jos puolet Turun, Helsingin ja Rauman telakoiden kapasiteetista käytettäisiin tähän, karkeasti 1–2 GWe verran uutta ydinvoimakapasiteettia voisi valmistua niiltä vuosittain**. Näitä voisi tukea Mäntyluodon telakka Porissa, jolla on sekä tarvittavaa osaamista että sertifikaatteja myös ydinlaatuisten painekomponenttien valmistamiseen. Tahti vastaisi karkeasti yhden Olkiluoto 3 -kokoisen (1,6 GWe) reaktorin valmistumista joka vuosi. Tämä on täsmälleen sellainen vauhdinmuutos, jota yhteiskunnan syvä dekarbonisaatio vaaditussa aikataulussa tarvitsee.

Kelluva ydinvoimalautta (FNPP, Floating Nuclear Power Plant) voidaan hinata mihin tahansa sijoituspaikkaan, kunhan sinne pääse vesitse, joten sijoittaminen on poikkeuksellisen joustavaa. Tämä mahdollistaa myös paljon nykyistä nopeammat projektit ja avaa käytännössä maailmanlaajuiset vientimarkkinat. Mikäli lautoilla tuotetaan sähköpolttoaineita (hiilivedyt, ammoniakki, vety), myös niiden kuljetus onnistuu pidempiäkin matkoja varsin kustannustehokkaasti, mikä edelleen laajentaa markkinoita.

Kustannukset ja niiden madaltaminen

Muutamat reaktorikehittäjät maailmalla suunnittelevat jo sijoittavansa reaktorinsa kelluville lautoille. Tärkeimmät edut tulevat kustannussäästöistä sekä valmistuksessa että sijoituspaikan valmistelussa, sijoittamisen joustavuudessa sekä tuotannon nopeassa kasvattamisessa telakoiden, konepajojen sekä näiden olemassa olevien toimitusketjujen ja verkostojen avulla. **Potentiaali pääomakustannusten madaltamiseen on merkittävä, arviolta jopa 50 % paikalleen rakentamiseen verrattuna ja jopa 75 % verrattuna viimeaikaisiin FOAK-hankkeisiin Euroopassa ja Yhdysvalloissa**.

Pääomakustannus (CAPEX) olisi arviolta noin 2500 €/kW. Tätä voidaan tulevaisuudessa madaltaa edelleen kehittyneempien reaktoreiden ja massatuotannon avulla. Sähkön vertailuhinnan (LCOE) osalta tämä tarkoittaisi todennäköisesti alle 40 €/MWh tasoa. Mikäli myös lämpöä myydään, esimerkiksi sähkön ja lämmön yhteistuotantona (CHP) kaukolämpöverkkoon, vertailuhinta pienenee edelleen.

Aluksen koko ja reaktoriteho vaikuttaa kustannukseen merkittävästi. 300 MWe tehoinen lautta voi maksaa puolet siitä, mitä 1200 MWe tehoinen lautta maksaisi. Tämä käytännössä kaksinkertaistaa pienemmän aluksen per MW-hinnan. Massatuotannolla tätä erotusta voidaan pienentää, sillä sarjatuotannon hyödyt voivat laskea sekä valmistamis- että luvituskustannuksia per alus.

Puhdasta vetyä voidaan tuottaa alle 2 €/kg hintaan, ammoniakkia alle 300 €/tonni ja lentokerosiinia alle

90 € per öljyekvivalentti barreli (boe). Nämä hinnat ovat kohtalaisen kilpailukykyisiä fossiilisten vastineidensa kanssa jo ennen 2021 Euroopan energiakriisiä, ja huomattavasti matalammat mitä ainakaan lähitulevaisuudessa on saatavissa tuuli- tai aurinkoenergian avulla, puhumattakaan näiden epätasaisen tuotannon vaatiman varastoinnin kustannuksista.

Mankala-mallilla ja valtion tuella riskejä ja rahoituksen kustannuksia voidaan pienentää. Tämä alentaa yllämainittuja vertailuhintoja entisestään, etenkin ensimmäisille laitoksille, joissa rahoituksen kustannus näyttelee erityisen suurta roolia. Myös kehitteillä olevat seuraavan sukupolven ydinvoimateknologiat, kuten sulasuolareaktorit, voivat pudottaa kustannuksia vielä huomattavasti kaupallistuessaan.

Markkinat

Globaalisti sähköistyminen tulee etenemään kiihtyvää vauhtia. Tämän lisäksi tulemme tarvitsemaan vähintään kokoluokkaa miljardi tonnia puhdasta vetyä vuosisadan puolenvälissä, jos aiomme tehdä merkittävän loven ennustettuun fossiilisten polttoaineiden kulutukseen. **Tämän vedyn valmistus tulee käyttämään karkeasti puolitoistakertaa (noin 40 PWh) nykyisen globaalin sähkönkulutuksen (~27 PWh).**

Eurooppa on keskellä pahenevaa energiakriisiä. Ydinvoimaloiden ennenaikainen sulkeminen ja sääriippuvaisen tuotannon lisääminen on johtanut kasvaneeseen riippuvuuteen Euroopan ulkopuolelta tuodusta maakaasusta. Tästä kaasusta noin 40 % (~1500 TWh) tulee Venäjältä, joka käy hyökkäyssotaa Euroopan ovensuussa Ukrainassa, jonka saatavuus on jatkossa kyseenalainen. **Niinpä Euroopassa tulee olemaan kasvava, satojen gigawattien, tarve puhtaalle, joustavalle ja toimitusvarmalle sähköntuotannolle sekä sähköpolttoaineille.** Viimeisen vuoden aikana kriisiytynyt tilanne on johtanut tehdyn energiapolitiikan kriittiseen arviointiin, ja ydinvoiman hyväksyttävyys on monissa Euroopan maissa nousussa.

Suomessa on kasvava tarve puhtaalle energiantuotannolle. Olkiluoto 3 voimalan käynnistys auttaa tuontiriippuvuuden pienentämisessä, mutta ei poista sitä. CHP tuotantoa (sekä hiili että maakaasu) on poistumassa 2020 ja 2030 luvuilla merkittävästi, ja voi olla, että 70 vuotta täyttävät nykyiset ydinvoimalat eläköityvät vuosisadan puolivälin teinoilla, ainakin osittain. **Tuonnin ja eläköityvän tuotannon korvaaminen vaatii 40–60 TWh edestä uutta tuotantoa, eli 5–7 GWe ydinvoiman tyylistä lähes jatkuvasti täydellä kapasiteetilla ajavaa tuotantoa.** Osa tästä voidaan kattaa jatkamalla Olkiluodon ja Loviisan laitosten käyttölupia vuosisadan puolivälin toisellekin puolelle.

Kunnianhimosta riippuen sähköistyvä liikenne ja teollisuus tulevat tarvitsemaan 60–100 TWh uutta puhdasta sähköntuotantoa. **Sähköistyvä liikenne tulee tarvitsemaan 5–10 TWh (~1 GWe), metalliteollisuus noin 10 TWh (1+ GWe) ja (petro)kemianteollisuus välillä 40–80 TWh (5–10 GWe) pudottaakseen päästönsä lähelle nollaa.**

Myös metsäteollisuudessa on suuria mahdollisuuksia. Olettaen nykyiset prosessit ja laitokset, kymmenen suurinta sellutehdasta tuottavat merkittävän määrän biopohjaista hiilidioksidia, josta voidaan vedyn avulla jalostaa hiilivetyjä. **Prosesseihin ja vedyn tuotantoon uppoaa jopa 200 TWh (25 GWe) edestä sähköntuotantoa, jos tämä hiilidioksidi hyödynnetään isompien laitosten osalta sähköpolttoaineiden raaka-aineena.**

Sääntely, lait ja yleinen hyväksyttävyys

Kansainvälisen atomienergiajärjestö IAEA:n mukaan meillä on riittävät kansainväliset kehykset kelluvien ydinvoimaloiden pilotointiin. Tällaiset pilottiprojektit tarjoaisivat arvokasta tietoa ja kokemusta kaikista niistä asioista, joita voi nousta esiin. Suomen kontekstissa, nykyiset yksityiskohtaiset vaatimukset voivat olla ongelma, mutta ilmeisesti niitä ollaan tarkistamassa. Yksityiskohdista riippuu paljon. Millaista reaktoriteknologiaa käytetään, onko sijoituspaikka satamassa vai merellä, millainen on lautan konfiguraatio ja mitä lopputuotteita (esim. sähköä vai sähköpolttoaineita) se tuottaa?

Suomessa ei ole rakennettu, operoitu eikä säädelty kelluvia ydinvoimaloita, joten tehtävää riittää, etenkin ensimmäisen kappaleen kanssa. Reaktori ja voimala pitää luvittaa, samaten kuin sijoituspaikka ja laitoksen käyttäjä. Kun luvitus on tehty kerran, seuraavat samanlaiset ovat huomattavasti helpompia, etenkin jos ne sijoitetaan samalle laitospaikalle. Valtion, mikäli sitä kiinnostaa tämänkaltaisen uuden puhtaan energian vientiteollisuuden käynnistäminen Suomeen, olisi järkevää tarjoutua jakamaan näitä ensimmäisten laitosten huomattavasti korkeampia luvituskustannuksia. Tällaisen investoinnin panos/tuottosuhde voi osoittautua erinomaiseksi.

Ydinvoiman yleinen hyväksyttävyys on viime vuosina ollut ennätyskorkealla, ja monet puolueet ja poliitikot ovat siirtäneet kantojaan myönteisempään suuntaan, joskin Venäläisen teknologian suosio ja hyväksyttävyys on romahtanut sen hyökättyä Ukrainaan. Energiateollisuus näkee pienreaktorit erittäin tärkeänä osana Suomen vuoden 2035 hiilineutraaliustavoitetta[2]. Silti ministeriöissä tuntuu olevan liikkeellä ajatusta, että liiketoimintaympäristön ja lakien päivittämisellä pienreaktorit paremmin mahdollistaviksi ei ole kiire, koska projekteja ei ole ilmaantunut.

On kuitenkin todennäköistä, että projekteja ei ole aloitettu juuri siitä syystä, että liiketoimintaympäristö, lainsäädäntö ja sääntely koetaan epävarmoiksi. Niinpä ”projektien puute” ei ole syy olla kiirehtimättä välttämättömiä uudistuksia. Pikemminkin, koska tiedämme, ja energiateollisuuskin on sen selkeästi kommunikoinut, että näitä teknologioita tarvitaan kipeästi päästövähennyksiin, on projektien puute selvä merkki siitä, että pullonkaula asiassa on muualla, kuten lainsäädännön ja sääntelyn luomassa liiketoimintaympäristössä.

2 https://energia.fi/files/6320/ET_SMR-positiopaperi_092021.pdf

For the Reader

This study is the result of years of pre-planning, thinking, searching for funding and then of research, interviews, and writing. The initial spark emerged as I contributed for the groundbreaking study "*Missing Link to a Livable Climate – How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals*" in 2019 and 2020.[3] Shipyard-built floating energy barges powered by nuclear reactors were one of the technologies we presented in the study as potential game-changers for both climate and clean energy access.

The cost-reduction potential and rapid scalability of shipyard manufactured floating nuclear power plants was very exciting, as it was precisely the type of step-change the world needs in clean energy production. Another angle was the Finnish situation, where we have a lot of expertise in most of the relevant fields and could perhaps kickstart a whole new industrial sector from a significantly better position than many of our peer countries. This industrial sector would bring jobs and prosperity both to Finland and to prospective customer countries by providing them with affordable, reliable, and clean energy at large scale. My brain started to think big.

Urgency was increased as COVID-19 pandemic took the world by surprise, and as the struggle of cruise line companies became apparent. A lot of Finnish shipyard output has recently been in cruise-ships, and nobody knows how the demand for such vessels will develop in the coming years and decades. In 2020, the situation looked dire, although it has now improved.

Finding funding for such a novel and relatively unknown topic was not easy. Maritime industry had just been hit hard by Covid, and the energy industry seemed to think that while this was an interesting topic, it was also something too far out in the future to be relevant now. Yet in the last couple years, this topic has been gathering international attention more and more, with multiple actors revealing intentions in building floating nuclear power plants for various purposes.

3 Lucid Catalyst 2020, https://www.lucidcatalyst.com/hydrogen-report

I decided to press on, and eventually proposed the study for the Ecomodernist Society of Finland as part of their theme of "Nuclear in New Ways". Together we managed to secure funding for the study from Quadrature Climate Foundation (UK) and the Rodell Foundation (US), and so the Ecomodernist Society of Finland commissioned this study from Think Atom[4]. Thank you all for the faith and support.

The study involved interviews with most of the key stakeholders in Finland, as well as international experts. The interviewees acted as experts in their field rather than representatives of their company or organization. Interviewees came from Fortum, Enersense / Pori Offshore Construction, Helsinki Shipyards, Meyer Turku, Rauma Marine Construction, Fennovoima, STUK, VTT, Platom, GE Hitachi, Ministry of Economic Affairs and Employment of Finland Energy Department, Kärnfull Next, Lucid Catalyst, and others. This study does not represent the views of the people and organizations interviewed, and any misunderstandings or misrepresentations I might have made are fully my responsibility.

Introduction – Scope of the Challenge and the Opportunity

Perhaps the most important thing to understand about the required scale of the energy transition is that we do not understand it.

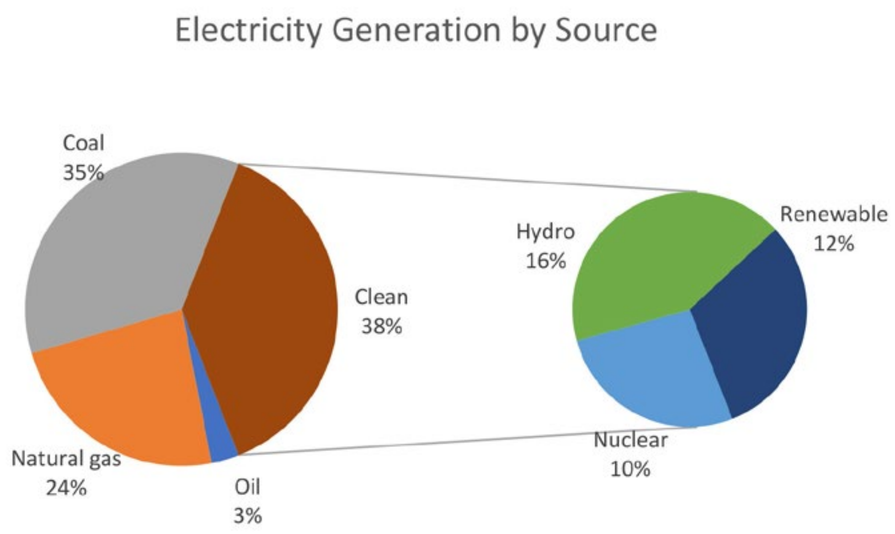
The world needs to decarbonize its energy supply as fast as possible. While doing that, it also needs to expand the energy supply significantly, especially in the developing world. The everyday climate hawk or clean energy advocate often misses a couple of aspects.

4 Full disclaimer: the author of the study is co-founder of ecomodernists in Finland and acts as a pro bono energy analyst for the organization.

Electricity Is Not the Whole Story

First, electricity is just 20% of our energy use. It took us roughly a century to get to 20% of our final energy use to be electricity, so the average electrification rate has been approximately two percentage points per decade. Electricity is still made mostly from fossil fuels, with a 62% share, so there is a full day's work just in decarbonizing our current electricity supply at speed needed.

Figure 1: Global electricity generation by source. Slightly over a third comes from low-carbon sources, the rest from fossil fuels. Data: BP2021



But what of the other energy use? Today, roughly half of our energy is used as heat for building heating, cooking, and industrial processes. About a quarter is used as liquid and gaseous fuels, mainly in transportation, heavy machinery, and other uses. This "non-electric" energy use is supplied 90% with fossil fuels, with bioenergy accounting for most of the remaining 10%.

Overall, roughly 84% of our primary energy came from fossil fuels in 2020.

Electrification Has Bottlenecks and Limits

Second, while the electrification rate might accelerate in the coming years, this rate has bottlenecks. The number of applications that can be "electrified" at a relatively low cost is limited. These have a couple of root causes. One is techno-economic. It might be technically hard or costly to shift a specific process or activity powered by oil or gas or coal to work with direct electricity – even if there is a realistic opportunity.

We are also stuck with our inherited infrastructure. In many situations, there is no realistic opportunity to electrify something. Any activities we do are done partly at the limits set by our current infrastructure, and rebuilding or changing that infrastructure is often both expensive and time-consuming. For example, the energy-throughput capacity of European gas pipelines supplies much of the heating and cooking energy in mainland Europe. Replacing it with electricity would require a significant overhaul of the regional transmission capacity and the local grids, including household fuse boxes, home appliances, and building heating methods. Not to mention dispatchable generation capacity to meet the increased demand in each country and region.

The estimates vary, but around half (+/-10%) of our end energy use will be hard to electrify. In these use cases, we will need to shift from fossil fuels to clean e-fuels. Manufacturing these fuels will require energy. Due to the inevitable losses involved, the amount of heat and electricity needed might be much more than we would use as direct electricity. So, while electrification often improves efficiency, the need to produce e-fuels will decrease our overall efficiency. This is important as it sets the required level of ambition for our hydrogen and e-fuels policies and investments.

Investment Cycles Matter

Third, there are convenience and investment cycles. We humans, and the organizations we have built, operate with certain assumptions and conveniences. It is hard for us to change how we do things, often both economically and psychologically. If a regional utility has just invested in a new coal plant, it will not be able (nor willing) to scrap that new plant while it has not been amortized or has decades of usable operational life left in it. Or, if a family has just invested in a new petrol-fueled car or an oil boiler for heating, they might not have the resources to re-invest into something else for a decade.

Indeed, a chemical plant might have an investment cycle of multiple decades. Suppose a new cleaner process or technology becomes commercially available in 5 years, but the investment is needed today. In that case, it might lock the old, dirtier process in for the next 30 years.

We Need High Net Energy

Fourth, as a society, we cannot switch to lower quality or more expensive primary supply of something as fundamental as energy. Pretty much by definition, this means a lower level of economic activity and productivity, which is something our society is currently not well-suited to handle. Indeed, we need a growing net energy supply to expand our economy and improve our living standards while reducing our environmental footprint.

Net energy becomes especially relevant when we start to make e-fuels at a large scale. Roughly half of the energy gets lost in the conversion process (electricity to hydrogen and then to ammonia and hydrocarbons). We are already trying to replace high-net energy fossil fuels with lower net-energy wind, solar, and bioenergy, as well as lower quality oil and gas deposits. When we try to replace some of our most significant sources of primary fuels – oil and gas – with synthetic replacements, the amount of net energy received from those fuels becomes crucial. With nuclear, we can produce e-fuels that provide significant net energy for society.

The World is Not the West

Finally, our energy use is growing, especially in the developing world. While the wealthy population living in rich countries can entertain the thought of decreasing their energy use as efficiency steadily improves, this only applies to a small subset of humanity. The vast majority of people desperately need more energy to increase their living standards and rise out of poverty.

We should not just replace our current fossil energy supply with cleaner energy sources but also expand that energy supply significantly. How significantly? While estimates vary, most are likely underestimating the growth that the developing world will aim to achieve. Most scenarios are done by rich western economists who rarely ask the Global South what they plan regarding their economic growth.

There are three main drivers for this. First, non-OECD energy use per capita is, on average, less than a third compared to OECD, so there is a lot of room to grow. Second, OECD countries have a population of around ~1.4 billion, while non-OECD countries have ~6.5 billion. Third, most projected population growth (adding 2 to 3 billion by mid-century) will happen in non-OECD countries.

To summarize, a citizen in a non-OECD country has much more to gain from increasing her energy use as she is still lacking many of the things we take as necessities, such as reliable electricity and transportation. There are also over four times more of these people looking for ways to improve their lot, and they are also growing in population as today's adults will be living much longer. It would not be out of the question to say that there is demand for doubling or even tripling our current energy supply by mid-century, mainly driven by non-OECD countries.

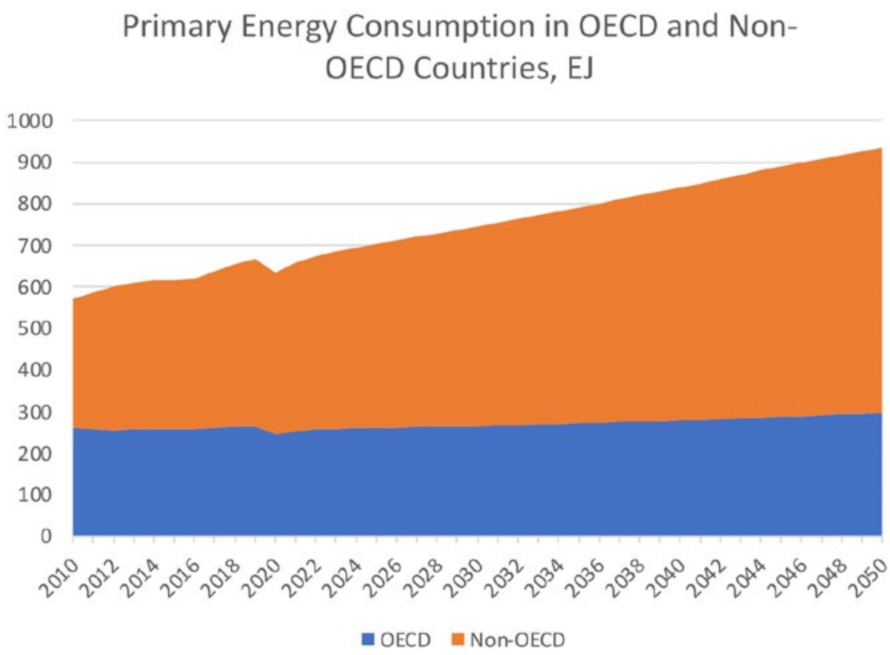


Figure 2: Projection of energy use in OECD and non-OECD countries through to mid-century, Exajoules. Image: EIA IEO2021.

Global Scale

As mentioned above, global energy demand will grow. There are a lot of projections and scenarios on the energy future of humanity available, but few see our energy supply doubling (let alone tripling) by 2050. For perspective, this study will present two "extreme" projections from credible institutions, a high fossil fuel case (EIA 2021) and a low fossil fuel case (DNV 2021).

The US Energy Information Agency (EIA 2021[5]) recently projected a nearly 50% increase in world energy demand in their reference scenario, up to over 900 exajoules. The High Economic Growth scenario saw global energy consumption almost doubling from 600 EJ today to over 1,100 EJ by 2050.

The energy consumption in non-OECD countries roughly doubled from 300 EJ to 600 EJ. Fossil fuels' total use grew slightly from today, nuclear remained stagnant, and renewables more than doubled. So, while wind and solar see rapid growth, they fail to replace current fossil fuel use as energy use grows even more rapidly.

As shown in Figure 3, the EIA reference scenario sees fossil fuels growing significantly by mid-century, reaching levels well above 600 EJ. Higher fossil fuels use means higher emissions. If we aim to stay around 1.5 °C warming, our energy emissions should approach zero by mid-century.

The other end of our projections comes from DNV's 2021 Energy Transition Outlook[6]. As seen in Figure 4, their scenario assumes that global energy consumption will start to decrease after peaking in 2030. The scenario also sees wind and solar grow perhaps 15-fold by 2050. There is still 300 EJ of fossil fuel consumption by mid-century, which is incompatible with our climate goals.

5 https://www.eia.gov/outlooks/ieo/

6 https://eto.dnv.com/2021

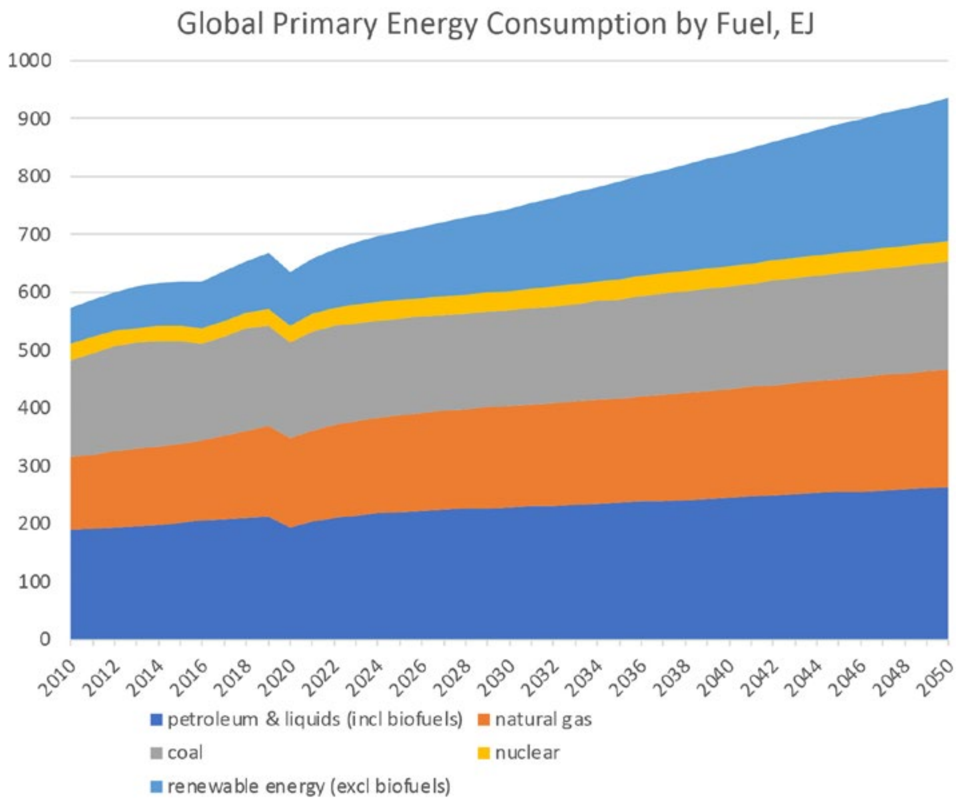


Figure 3: The primary energy consumption globally by fuel. Data: EIA IEO2021

Much of the fossil fuels in EIA's and DNV's scenarios are used in hard-to-electrify sectors.

To clarify the scale, let's take an example of how much of an impact producing one billion tons of clean hydrogen per year by 2050 would have on the fossil fuels in these scenarios (although DNV assumes quite a bit of clean hydrogen production already, at more than 200 million tons). The comparable energy content of one billion tons of hydrogen is around 120 EJ. This would replace 40% of fossil fuels in the DNV scenario and 20% in the EIA's reference scenario.

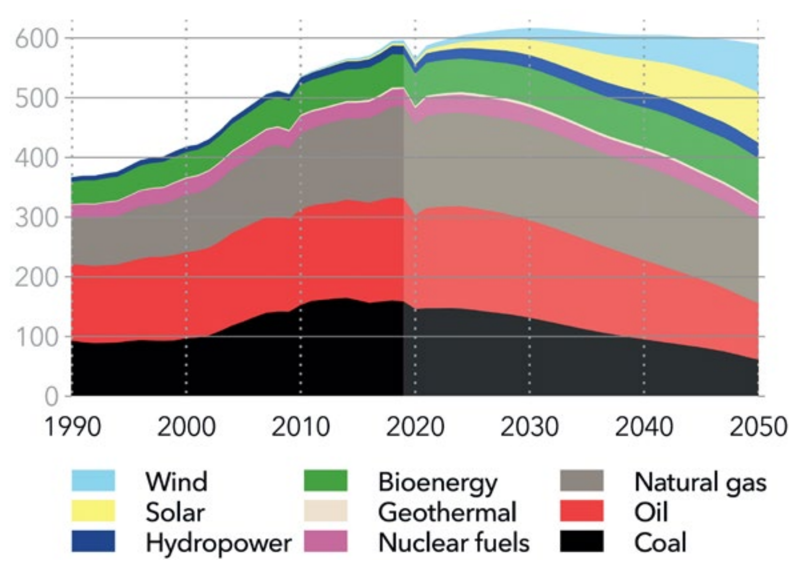


Figure 4: The energy transition scenario by DNV sees some 300 EJ of fossil fuels still being used by mid-century, even though they assume that global energy use will start to decrease after 2030.

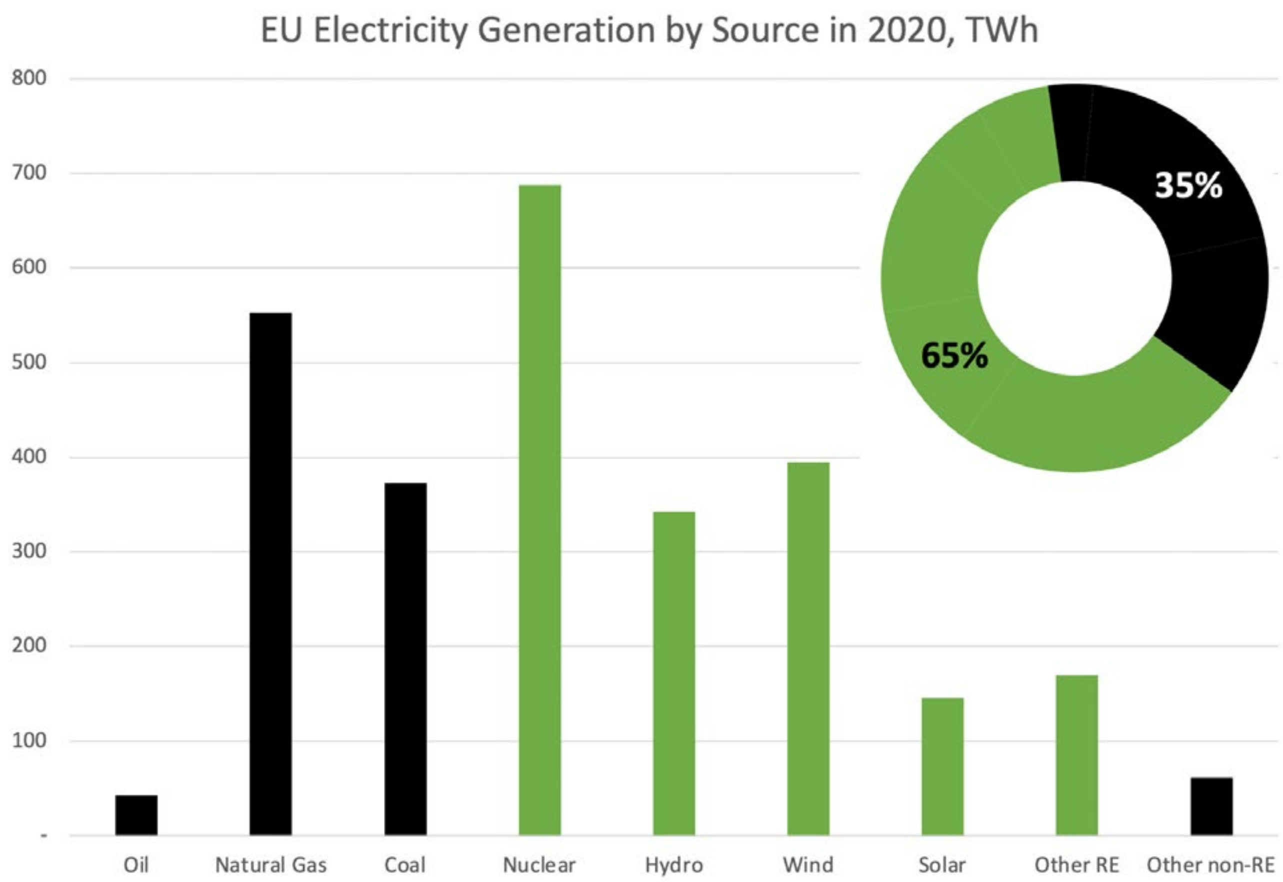
Yet, it would take some 40,000 TWh of clean electricity to produce this amount of hydrogen. Today, the world produces slightly over 10,000 TWh of low-carbon electricity out of 27,000 TWh of total electricity we consume. To decarbonize our growing electricity demand and produce enough hydrogen by 2050, **we need to grow all low carbon energy production 6 to 10 times from current levels in the next 30 years.** This is the global scale of the challenge and the opportunity.

European Scale

This study will discuss the European situation later, but below is the general picture. Roughly two-thirds of EU electricity comes from low-carbon sources, of which almost half is nuclear.

Fossil fuels cover roughly 72% of final energy use in Europe, and most buildings in Europe are heated with gas and oil. Road transport, shipping, and aviation mostly run on fossil petroleum products, and industrial processes run primarily on natural gas and coal (and electricity).

Decarbonizing just the European chemical industries and the fuels it produces to any significant degree will require more than doubling our electricity production from current levels. To reach maximum decarbonization, not just on the processes but also on the fuels, demand for clean power might grow 6-fold from today.



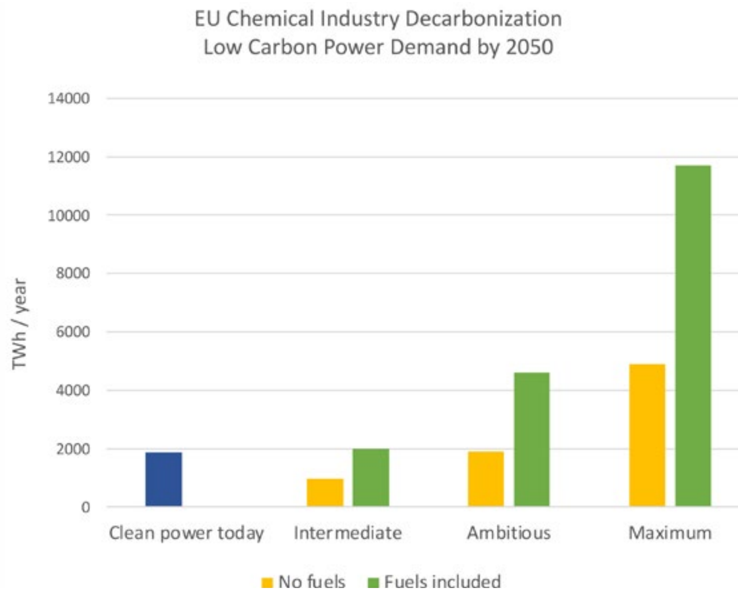


Figure 5: The low carbon electricity demand for the European chemical industry decarbonization. Ambitious gets us roughly 8% emissions reduction. Data source: DECHEMA 2017 - Low carbon energy and feedstock for the European chemical industry.

Europe has, of course, other industries and sectors besides the chemical industry that it needs to decarbonize. Road transportation is shifting towards EVs, metal and other heavy industry needs to get out of fossil fuels, building heating will need to change from gas and oil to clean energy sources, etc.

A recent meta-study[7] on the studies done on the future demand for clean hydrogen in Europe found out that by 2030, Europe would consume between 300 to 600 TWh of hydrogen. By 2050, this demand would grow to 1,500 to 2,250 TWh. Assuming an average efficiency of 75 % for electrolysis, these numbers translate to 400 – 870 TWh of clean electricity demand by 2030 and 2,000 to 3,000 by 2050.

EU has a goal of installing 40 GW of electrolyzers by 2030 within member states. In addition, the EU has suggested another 40 GW of electrolyzers in neighboring countries to import hydrogen from. These electrolyzers will require a clean power source, which would preferably produce full power closer to 8000 hours in a year. Yet many EU member states have been more focused on closing their operating nuclear fleets prematurely rather than building the necessary new capacity. In addition to the lack of reliable supply to run the electrolyzers, this is creating a severe grid reliability crunch that might worsen in the following decade, just as the demand for more clean electricity is accelerating.

7 https://gasgrid.fi/en/2021/12/16/finland-has-opportunities-to-become-the-leading-country-in-hydrogen-production/

European Energy Crisis Unfolding

In 2021 natural gas and electricity prices rose sharply in Europe. This increased fertilizer prices as well, even threatening the food supply. Clean hydrogen, and e-fuels produced from it, became competitive much earlier – if they were only available at scale. If high prices persist, new investments will happen, but those will take years. Who knows what will happen in the meantime? High energy prices drive nations into recessions while causing cost-based inflation on top of the inflation caused by the massive money-printing COVID-19 economic slump launched.

In early 2022, Russia invaded Ukraine, leading to escalating sanctions, potentially also for energy trade between Russia and Europe. 40% of Europe's gas and 25% of oil comes from Russia, and in some countries, those shares are close to 100%. The urgency to get more energy independent and secure the energy supply has grown to new levels, likely leading to a significant expansion of nuclear power.

Finnish Scale

As in most OECD countries, electricity has a higher share than the global average in Finland. Electrification has driven, and been driven by, rapid economic development and industrialization during the last century. The share of electricity varies country by country, as it is affected by the present industrial sectors and the availability of low-cost electricity. On average, electricity represents 28% of end-energy use in OECD countries[8], and Finland sits near the average with a 28.5% share of electricity in final energy use.[9]

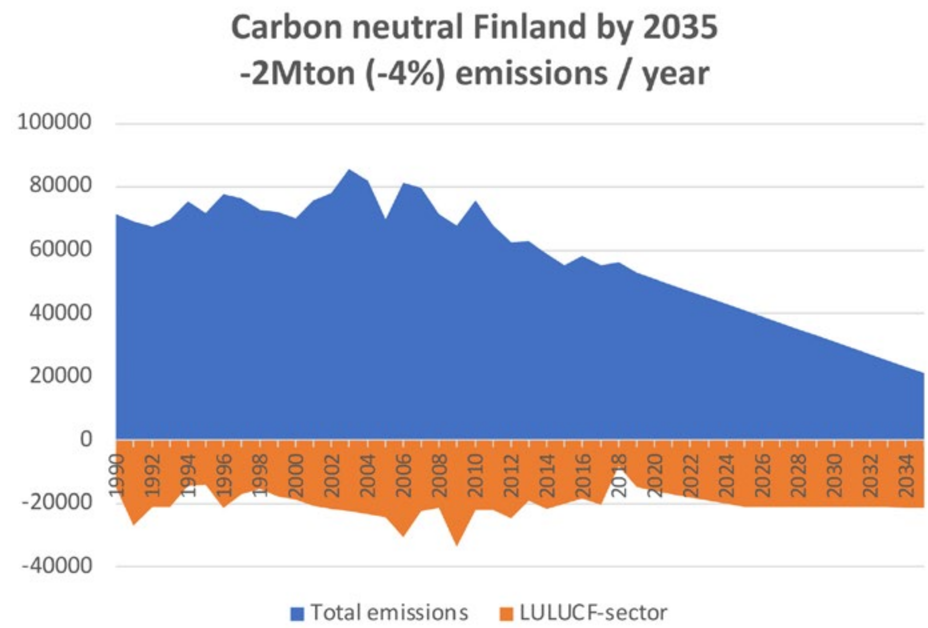


Figure 6: Historical and future CO2 emissions in Finland if we are to reach carbon neutrality by 2035. Historical data: Tilastokeskus.

While electricity in Finland is already relatively low carbon, averaging well below 100gCO_2-eq/kWh, the Finns still have pretty high (gross) emissions at around 10 tons per capita.[10] Only roughly 10% of an average Finn's emissions come from electricity. The primary sources of emissions for a Finn are transportation and other liquid fuels use, heating, industrial processes, and agriculture (including land-use emissions). Each category represents somewhere between 10 and 20% of total emissions, so they all need to be decarbonized to a significant degree for Finland to become carbon neutral by 2035 and then carbon-negative soon after, as is the Government's intention.[11] The Finnish forests act as a net sink for carbon, storing between 15 and 25 million tons of CO_2 per year (net), depending on the intensity of harvesting and logging in any given year.

8 IEA, OECD total final consumption by source, 1971-2018, IEA, Paris https://www.iea.org/data-and-statistics/charts/oecd-total-final-consumption-by-source-1971-2018

9 Official Finnish Statistics (SVT): Energian hankinta ja kulutus [verkkojulkaisu]. ISSN=1799-795X. Helsinki: Tilastokeskus [read: 21.7.2021]. http://www.stat.fi/til/ehk/tau.html

10 Roughly a third of this is sequestered into Finland's growing forests. Depending on the amount of logging done on any given year, this can vary significantly.

11 Most of this carbon negativity is planned to be done with the help of those carbon sinks in the forests.

To achieve carbon neutrality by 2035, the general trajectory should look something like Figure 6. From another perspective, Figure 7 shows us how the next three decades look for Finland in terms of demand for new, clean electricity and energy production.

As seen in Figure 7, pre-Olkiluoto 3, Finland imported around 20 TWh of electricity per year. By mid-century, our elder nuclear power plants will be turning 70 years, and some of them might face retirement. By mid-century, Finland will also retire most of its fossil-fired CHP capacity, along with wind turbines built before 2025[12]. These can add up to 65 TWh of demand arising from retirements and the need to reduce imports, of which OL3 will supply 13 TWh.

There is also new demand that needs to be met at around 65 TWh, perhaps even more. Road transportation will electrify (5-10 TWh), the steel mill at Raahe will shift away from coal (~10 TWh), and the (petro) chemical industry will clean up its processes and some of its fossil fuel feedstocks (~45 TWh)[13]. Depending on

12 Assuming an average operative lifetime of 25 years for wind turbines.

13 The low-carbon roadmaps of Finnish industry can be found at https://

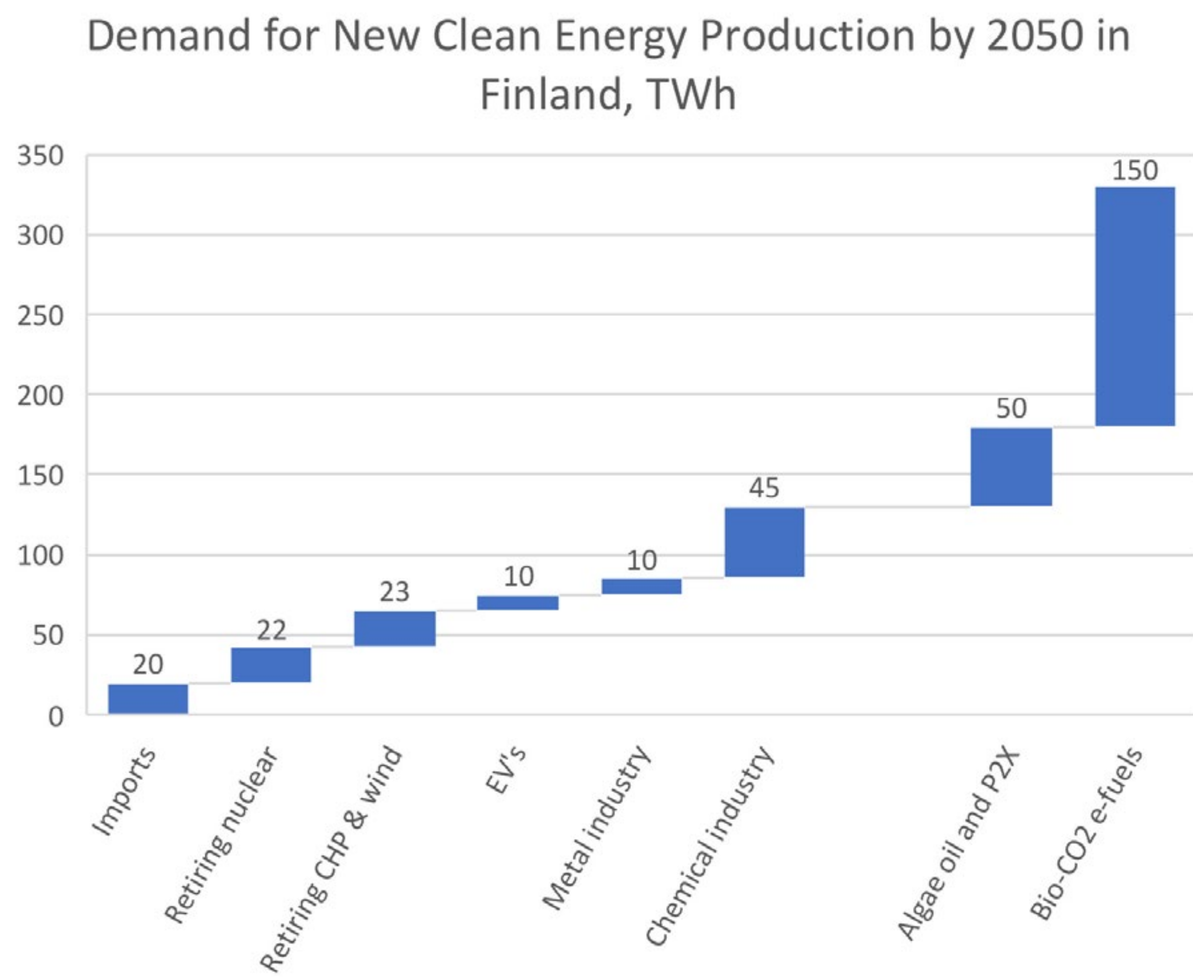


Figure 7: New demand arising in Finland by mid-century.

the scale of replacing the fossil feedstocks, the demand could also be much higher, closer to 100 TWh. Most of the need will be for reliable or flexible capacity that produces relatively low-cost electricity.

The most significant part of the potential demand pie is the potential for making hydrogen and using bio-based CO_2 from Finland's pulp mills as the carbon source for e-fuels. According to a recent report by Lappeenranta University and others, the scale is up to 200 TWh demand for clean hydrogen production[14]. Indeed, nothing prevents Finland from becoming a significant net exporter of low-carbon energy products. In addition to carbon-neutral hydrocarbons, this category also includes fuels and chemicals such as ammonia, made from hydrogen and nitrogen. Ammonia is already used at a large scale and has many potential uses in the future, such as a marine shipping fuel. Table 1 summarizes some of the different types of fuels and their possible uses.

tem.fi/julkaistut-tiekartat
14 https://www.lut.fi/documents/27578/600639/Carbon+Neutral+Finland+-report+EN.pdf/eb6a9e1a-411e-47f2-b0b0-a6e737f5ac70

A Hydrogen Pipeline to Germany?

In September 2021, Finland's minister of employment and economic affairs, Mika Lintilä, said that perhaps Finland (along with Sweden) should build a hydrogen pipeline into Germany. A hydrogen pipeline will only make sense if it has significant throughput of hydrogen, in the 5–10 gigawatts scale or more. For comparison, Nord Stream 1 (NS 1) has a maximum capacity of 55 billion m^3, which equals roughly 615 TWh annual, or 70 GW of constant capacity. NS2 has a similar capacity. This hydrogen would need to be produced, requiring some 6–12 gigawatts of reliable power and electrolyzer capacity. If done with offshore wind, both the energy production capacity and electrolyzer capacity would need to double as they would operate at lower efficiency due to wind production variability. We would also need enormous storage facilities to keep hydrogen constantly flowing in the pipeline, even on days with little wind.

Table 1: Some e-fuels and their current and potential future use cases.

E-fuel	Type	Current Uses	Some new, potential future uses
Hydrogen	Pure H_2	Chemical and fertilizer industry feedstock, oil refining	CO_2-neutral steel making, biofuels enhancing, hydrogen vehicles, industrial process heat, and feedstock for all the fuels below.
Ammonia	Nitrogen+H_2	Fertilizer, chemical & plastics industry, refrigerant, explosives, etc	Marine shipping, gas turbines (power), co-firing coal power, a medium for hydrogen transport & storage.
Methane	Carbon+H_2	Power production, chemical & plastics feedstock, industrial heat, heating & cooking	Transportation fuel for hard-to-electrify vehicles.
Methanol	Carbon+H_2	Plastics, paints, parts, construction materials.	Transportation fuel for cars/trucks, shipping, cooking, and heating fuel.
Jet-A	Carbon+H_2	Aviation fuel	
Diesel	Carbon+H_2	Transportation, agriculture & forestry & construction machinery, power production	
Gasoline	Carbon+H_2	Light road transport (cars)	Long-term, likely decreasing use as EVs proliferate.

Drivers for Change

In 2020, the main drivers for this study were climate and Covid-19. Climate, because it was becoming clearer by the day we need a step-change in the rate of clean energy production, and shipyard manufactured nuclear offered one of the most exciting options. Covid-19, because the situation with cruise companies and their orders for new cruise ships started to look bleak. Since then, additional drivers have emerged.

First, the emission prices in the European ETS market took off like a rocket, growing by an order of magnitude in just a few years. First, the price jumped from 5 €/ton in 2017 to 20 €/ton in 2019, then to 80+ €/ton between late 2020 and early 2022. It remains to be seen whether these high prices will persist in the coming years, but these levels were not supposed to emerge before the 2030s.

In the second half of 2021, Europe entered a surprise energy crisis. Natural gas prices spiked, as did electricity, again by an order of magnitude. With both the fuels and their emissions suddenly costing ten times as much as they did just a while ago, the investment horizon suddenly looks different.

In early 2022, the EU Commission published their Complementary Delegated Act (CDA) to include nuclear energy and natural gas in the European Taxonomy for sustainable investments. While the final paper includes some strange conditions for nuclear, and while it can still be voted down[15], this is overall a net positive for financing nuclear projects in Europe.

As the final driver, Russian president Vladimir Putin did what most of us thought unthinkable and invaded Ukraine. Several days into the war, many European leaders, Germany included, started to question their energy policy choices, especially those that led to greater dependency on fossil fuels flowing uninterrupted from Russia. The Europeans are paying for these fuels, essentially funding Putin's war machine. Suddenly, energy security, reliability, and independence were on everyone's lips, leading to further support for nuclear power.

15 At the time of writing, they have not yet voted on this, but by the time of publication, they have.

Summary

There will be demand for 100-300 TWh of clean, low-cost electricity in Finland for various purposes and up to two orders of magnitude more in Europe. Thanks to the rise of a new wave of environmentalism[16] that supports nuclear technology due to its many benefits and several other events converging recently in Europe, the public and political support for nuclear has been increasing and opposition decreasing.

Globally, demand for affordable energy – electricity and fuels – is growing, especially outside OECD countries. From a climate and environmental point of view, we need to supply that energy with minimal emissions and a small material and ecological footprint. For most of these purposes, low-cost, rapidly deployable semi-mobile floating nuclear power plants (FNPPs) would provide an ideal choice.

The Next Level – Why Shipyard Nuclear?

"It's the economy, stupid."
James Carville, future president Bill Clinton's election strategist, 1992

For Scaling, Cost Is Critical

The critical factor in manufacturing and using clean e-fuels at a large scale is cost. There is much less demand for high-cost hydrogen than for low-cost hydro-

16 See for example https://www.replanet.ngo/

gen, simply because the cost is crucial for most people and companies. We need low-cost clean energy, as the cheaper the alternative is, the faster we can replace fossil fuels and scale up production. On the other hand, scaling production up will often bring down the cost due to learning curves, series manufacturing, and other benefits of large scale.

One of the essential advantages of fossil fuels is their low cost[17], and cheap energy is one of the critical enablers of our industrialized, modern society. We cannot replace low-cost energy with high-cost energy and expect our economy to sail on smoothly. It won't, as our society is built on growing productivity, which depends on low-cost and high-quality energy supply and high efficiency. Higher energy cost means lower productivity and less economic activity, leading to lower living standards, energy poverty, joblessness, and eventually social unrest and political polarization.

So, how can we make various clean energy products at a massive scale and low cost? Depending on our level of ambition, there might be demand for 100-300 TWh of new annual electricity production by around mid-century just in Finland. One gigawatt of reliable capacity produces 8 TWh of electricity. **To have 100-300 TWh of new production online by 2050, we need 400 to 1,200 megawatts of added reliable capacity per year for 30 years**. That annual capacity addition needs to be roughly doubled or more for wind. Further, having a stable and reliable energy system with a large share of wind will be much more expensive than just the cost of wind turbines.

In Europe, let alone globally, the demand growth for clean energy is accelerating, meaning an enormous export potential. **With a growing market for clean electricity, heat, hydrogen, and e-fuels, there is an opportunity to start building nuclear plants in a way that lowers their costs rapidly and significantly**. It is abundantly clear that the current practice of constructing one-off, first-of-a-kind reactor projects once a decade or two is both insufficient and overly costly.

Constructing nuclear reactors in series is one opportunity to lower costs[18]. Still, this study discusses taking this to the next level: manufacturing and assembling reactors and their systems in series at highly productive shipyards and deploying them as floating and versatile energy production platforms. As we learn later, there is a significant opportunity to lower both CAPEX and OPEX costs with this deployment model.

But it's not just about the nuclear island and its costs. Nuclear power is a very high-quality electricity source as it is both reliable and dispatchable and relatively low cost in most cases. But to make energy products other than electricity or steam – such as liquid or gaseous fuels – additional facilities are needed. These facilities include electrolyzers, seawater desalination, nitrogen or carbon capture, and Haber-Bosch or Fischer-Tropsch synthesis units. Assembling and manufacturing these in a highly productive environment like a shipyard into a compact and cost-effective platform such as a floating barge and then siting it in a near-shore or offshore location can significantly cut CAPEX and OPEX costs.

To make e-fuels, there will also be losses in the conversions from one energy carrier to another. Depending on the process and end-product, roughly 50% (+/- 20%) of the energy in the electricity is lost when it is converted into ammonia or hydrocarbons. So, if electricity costs 5 cents per kWh, the losses alone can increase the cost of the end-product closer to 10 cents per kWh, roughly double what we pay for crude oil-based fuels (without taxes and fees).

In addition to the costs from conversion losses, we also need to invest in electrolyzers and other facilities. To minimize their share in the overall cost of the end-product, they should operate close to 24/7. This is

17 One can argue that this is partly due to them externalizing their costs, for example those caused by particulate pollution and climate change acceleration, quite effectively.

18 For example, the Barakah four-reactor NPP project managed to more than halve the cost between the first unit and the fourth unit.

where the otherwise relatively low-cost wind and solar take a stumble. They produce energy depending on weather and time of day and season, leading to lower usage for the other facilities. This can increase overall costs significantly[19].

To make competitive synthetic e-fuels with clean electricity running electrolysis, the cost of reliable electricity needs to be around 2 cents per kWh, preferably even lower. This cost level, combined with low-cost electrolyzers and the more efficient high-temperature steam electrolysis (HTSE), leads to a hydrogen cost close to 1 € per kg. The cost of building, operating, and financing new nuclear needs to drop dramatically from current levels, especially in Europe and the US.

Luckily these factors can all be mitigated, and costs brought down if we focus on those. Both shipyard manufacturing and offshore siting have significant potential to lower the costs of new nuclear. There is also an important opportunity for Finnish shipyards, both as a business case and to help with the global climate effort.

Cost Reductions Due to Shipyard Manufacturing and Offshore Siting

Shipyards are among the most productive settings that humans have invented for constructing large things such as ships and offshore platforms. Constructing something on-site in the middle of nowhere with workers and subcontractors coming from all over the region is one of the least productive settings we have. Sometimes this can't be avoided: large buildings, airports, highways, or metro tunnels need to be built where they are to be sited and used, as moving them afterward is impossible. But one can argue that when avoidable, perhaps it should be.

This limitation does not apply to facilities that produce energy that can relatively easily be transported to where energy is needed. Ships the size of several city blocks can be constructed at shipyards, and they can readily be moved to another location. Nothing prevents us from designing and building a ship or a floating platform with one or several nuclear reactors designed and built into it. For brevity, this study will refer to these multi-product energy production platforms simply as floating nuclear power plants, or FNPPs[20].

This approach turns many of the current constraints and assumptions regarding nuclear construction on their head. As it is such a novel idea, it is also natural to view it with healthy skepticism. There are a lot of problems and questions to solve, but there are also a lot of solutions already in existence for those problems. The key target is to **make nuclear power much lower cost than today without compromising public health or the environment. This enables us to replace fossil fuels use faster and avoid catastrophic climate change.**

19 With assumptions held the same, going from roughly 93% capacity factor to ~45%, the cost of hydrogen increases by 80%.

20 In the oil and gas sector, these types of vessels are called FPSOs, which comes from "Floating Production, Storage and Offloading".

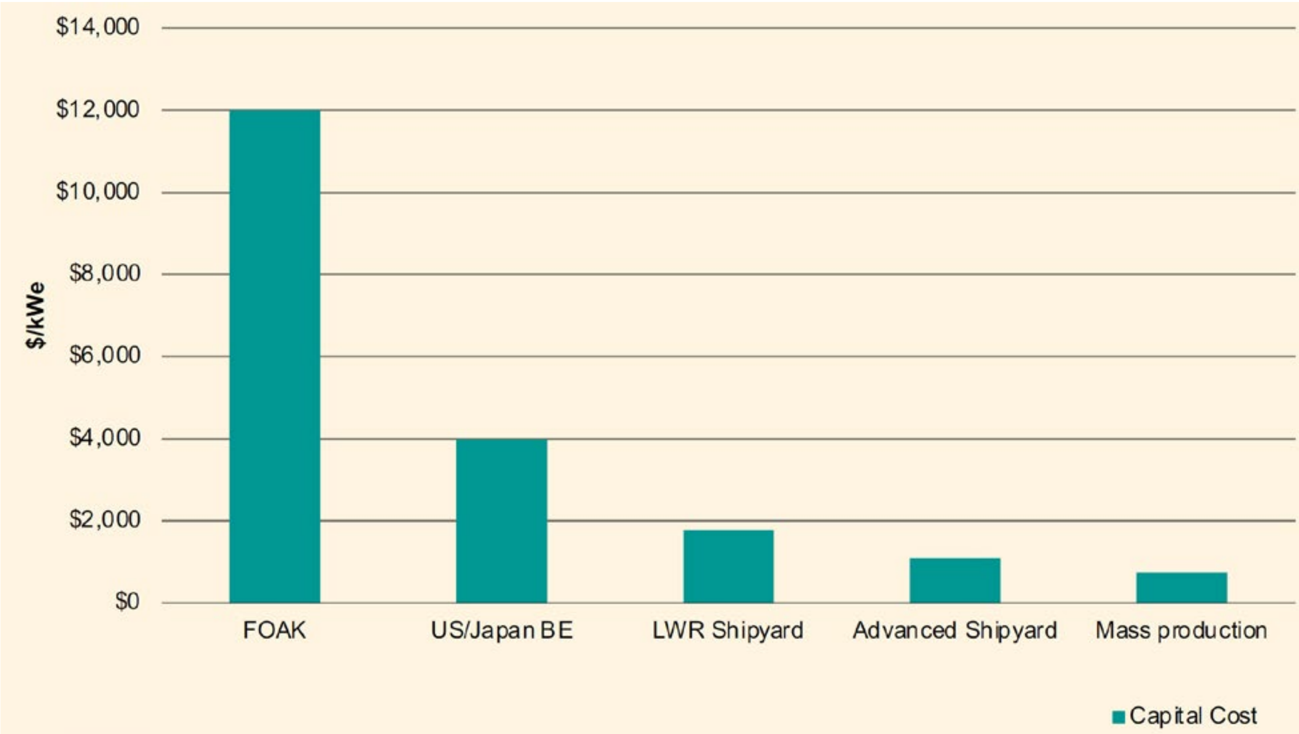


Figure 8: Cost-reduction potential with bringing nuclear manufacturing into highly effective, modern shipyards and floating offshore vessels. Image Credit: LucidCatalyst 2020.

Lucid Catalyst first quantified the cost reduction potential in the ground-breaking study Missing Link to a Livable Climate (2020[21]). The overall picture can be seen in Figure 8.

Even without reaching this full potential in cost reductions, one can easily see that this can be a gamechanger in the true sense of the word. If we can produce reliable, clean energy production facilities at costs near €2,000 kWe, it is undoubtedly something worth seriously inspecting. It is fascinating as this is not some novel, untested future technology in a lab somewhere. This is about taking practical lessons and expertise from one industry (shipyards and offshore activities) and applying them to another field (nuclear energy) to reduce costs ruthlessly. In essence, it is something we humans have done multiple times already, not least in bringing down the costs for wind and solar energy production.

The cost reductions mentioned above are for serial production, not for first-of-a-kind (FOAK). The FOAK will bear the burden of all the work in licensing the design and the new type of site. Given that this is also novel for the Finnish regulator STUK, the first one will be labor-intensive and expensive. This should be mitigated by the government, for example through cost-sharing, as much of the work goes into building competence also with the regulator, and the long-term benefits are significant.

Even so, by planning the design and licensing and doing it in a smart way, the costs can be mitigated, even for the FOAK, and more so for NOAK facilities. For example, there is a tendency in the nuclear industry to license a single component for a single use-case and single place in the system. This causes the same component to be licensed again and again for slightly different use-cases and is both slow and expensive.

21 The author of this study was a contributor in the Missing Link to a Livable Climate. Report can be found at https://www.lucidcatalyst.com/hydrogen-report

Yet one can (and arguably, should) license the component for a certain level of requirements to be used throughout the system, the module, the plant, and even future modules and plants as long as they are similar. This way it doesn't need licensing for every single use, but perhaps just a notification for the regulator where it is used, and if changes are made, only the changes are sent for approval instead of doing the whole re-license work. This can be done at multiple levels as well. A certain module can be licensed to be used on multiple vessels with set design parameters, and, as long as the interconnections between modules are set and standardized, they can be mixed with other modules with compatible connections and licensing. This requires significant thinking and planning ahead, but can decrease cost significantly down the road.

Why is this not happening? A good question. Perhaps, for an individual design engineer, it is a bit simpler and easier to license a component for the particular use-case that is needed at the moment. He doesn't have the large picture and does not realize the overall significance of the choice he makes. Going for a more extensive license would mean more work at that moment, so it might be easier to discount it in the heat of the moment. In the large scale, the effect multiplies, potentially throughout supply chains, costing very significant amounts of time and money.

The key would be to have the overall licensing in mind when doing the design work, and to plan how design and eventually licensing is done. So not just "design licensing" but also "designing the licensing." Otherwise, we are doomed to license the same or similar components over and over, wasting time and paying millions along the way.

The potential for the climate is enormous and therefore deserves a thorough consideration with an open mind. From a Finnish perspective, if this potential exists, we have an excellent opportunity to seize a significant piece of it, thanks to our existing industrial capabilities and institutions as well as our significant pool of skilled experts and professionals in the nuclear field. Others are already pursuing this opportunity, although mostly still in the early stages. Our decisions today will determine whether we will be the seller or the buyer of these products in the future.

Modular, Standardized Multipurpose Design

We build large ships from modules that are attached to each other at shipyards. With clever design, FNPPs can be customized from modules to meet different needs.

The central unit would be the (perhaps passively safe) reactor module, which houses one or multiple heat sources (reactors) and would likely fill a significant part of the ship's hull. Depending on the design, the heat source could be of any compatible type: light-water, molten salt, gas-cooled, or something else. Other modules could include some of the following:

- steam and turbine generators,
- high-temperature energy storage such as molten salt,
- water desalination facilities,
- electrolyzers (low or high temperature),
- air capture unit for nitrogen,
- Haber-Bosch ammonia facility,
- Fischer-Tropsch facility for making hydrocarbons,
- storage facilities for the end-product(s).

As long as the connections and specs are standardized, one could customize different configurations depending on the customer's need and update the modules if new and better technology comes available relatively straightforwardly. This standardization would also allow companies to offer their specialized modules and help ensure their compatibility and safety with the rest of the modules and components.

So, a simple FNPP might have a heat source, a steam generator, and a turbine generator to supply a coastal city with electricity. Another might have two heat source modules, steam and turbine generators, an electrolyzer, a Haber-Bosch unit, an ammonia plant, and a desalination unit using electrolyzer waste heat as the energy input for the process. The platform could flexibly produce anything from electricity to hydrogen to ammonia to desalinated water and send the products to a coastal city or industrial facility via cables and pipelines or offload the ammonia into tankers for further transportation into markets.

It is also possible to have one ship producing electricity, transmit it to another vessel nearby and run the electrolyzers and other facilities there. There are some benefits and some setbacks to this approach. As a benefit, it could make designing, licensing, and manufacturing both of the ships more straightforward. The vessel with the nuclear facilities would not need to consider the presence of electrolyzers and other facilities, nor that of hydrogen, ammonia, or hydrocarbons in the intermediate storage.

The ship with the electrolyzers and other modules and storage facilities would not need to consider the immediate presence of a nuclear reactor. These ships might differ in the quality and licensing of their modules and parts. If this is the case, it might make sense to have one shipyard concentrate on building nuclear facilities and make the other ship(s) at another shipyard. One FNPP could also supply electricity to multiple vessels, each producing different end-products, perhaps even simultaneously. Having separate vessels for different purposes might also mean more flexibility in replacing, maintaining, or updating various facilities. A near-shore FNPP could also supply electricity to an on-land facility.

Building and operating multiple ships might be more expensive than running a single bigger, more complex ship. Further, the basic idea is to design the vessels so that the “nuclear island” is the only part requiring nuclear-grade licensing. At the same time, the rest of the ship would be “normal” industrial-grade – often at least as good as the nuclear grade, but a lot easier and cheaper to license and with much more suppliers. If this proves to be impossible for one reason or another, having multiple ships would circumvent this. Depending what king of licensing is needed for the site and the operator, having separate ships for the nuclear reactor and other facilities might make sense.

Indeed, with modules using standardized connectors and specifications, technology suppliers would have a larger market and more incentive to design different modules. Of course, another way would be to vertically integrate as much of the supply chain as possible and make custom in-house designs and connectors. This would require more capital, higher risk tolerance, and broader expertise. And even then, a standardized, modular approach in the design would make sense to enable easier customization of platforms depending on customer needs.

Manufacturing and Assembling vs. Construction

We humans have come up with several different ways to build big things throughout our history, from the Pyramids to The Great Wall to medieval castles and cathedrals to supertankers, hydro plants, and nuclear power stations. How we design and build things has a significant impact on our productivity (work done per worker hour), on materials needed, and eventually on the total cost of the product. One of the most productive settings we humans have come up with is the modern shipyard.

A modern shipyard is highly optimized for what it does, and it can have higher productivity than any other setting for building very large things.[22] A shipyard can optimize manufacturing stages and material inputs and outputs with complete tracking of their origin. They have integrated storage facilities, skilled working crews, in-house manufacturing facilities, design integration, quality control and inspection, and more. All this leads to higher productivity, same or higher quality with less effort, and lower risks compared to one-off on-site projects.

Bringing most of the project into a shipyard makes it a “product” instead of a project. The potential efficiency and productivity gains are among the major categories for cost savings when comparing FNPPs to on-land construction projects.

Fewer Materials

A nuclear power plant built on land requires a significant amount of concrete and rebar just for the foundation and buildings, and these can be a substantial part of the total cost. These do not apply to a floating vessel, and a large ship’s hull is mainly steel. While the reactor itself will likely have a similar cost to manufacture, whether it is sited on land or at sea, it represents a relatively small part of the total cost of a nuclear power plant.

Siting

Site development and civil works are roughly a fifth of the total CAPEX of a nuclear power plant. With a floating unit, there is no site preparation at a similar scale. Further, there is less human habitation around to be disturbed when siting offshore. Land is valuable, especially if near population centers and industrial zones need to be zoned for energy production. From a city-planning point of view, having industrial activities at non-permanent offshore locations or in a harbor nearby would free valuable land for other activities.

22 Larger than aircraft, which are also manufactured very efficiently.

The concept offers a lot of flexibility for siting, as the vessel can be towed almost anywhere there is a sufficient waterway. For supplying power for a city or other energy products for a coastal industrial park such as a refinery or chemical plant, it might be easiest to site the FNPP at a nearby harbor. They are already industrial zones with security in place, have demand for the products, and can transport the products to other locations. Harbors are often quite close to densely populated areas, as many large cities are on the coast, so non- or semi-permanent offshore units can supply them with various energy services.

FNPPs can be located at the harbor, near-shore, or further away, depending on what they produce. Especially with synthetic fuels production, the platforms can be sited even out at sea, similar to current oil and gas drilling rigs or offshore wind parks. If the product is electricity, heat, or desalinated water, it makes more sense to have the FNPP near the coast or harbor.

Further, the recent IPCC report[23] raised concerns about rising sea levels on coastal infrastructure, including nuclear power plants. The seriousness of this can be debated, as humans have been building seawalls for centuries and nuclear power plants have a tiny land footprint compared to the amount of energy they provide. Then again, as the rising sea level is something to worry about in general, having floating power plants might be an excellent idea.

Decommissioning and Recycling

While the operational lifetime of a floating vessel is likely significantly shorter than that of an on-land nuclear power plant, the decommissioning and recycling of materials can be much more streamlined. As the first FNPPs begin retiring sometime in the second half of this century, we can tow them to a single, specialized location for effective disassembling and recycling. There is no need to return the site to a “greenfield” or

23 https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/

even a "brownfield" state after decommissioning, as there is no site at all.

At a centralized "decommissioning shipyard," activated materials can be handled with due care and procedures, the reactor core removed and spent fuel managed appropriately, and the non-activated materials recycled for future use. Bringing the power plant to a central location for disassembly increases effectiveness and productivity compared to on-site decommissioning.

Non-Shipyard Specific Cost Reductions

Smaller Operation Crews

Having smaller crews is not a cost-saving directly related to shipyard building or offshore siting. Yet, it is a significant potential cost reduction that new nuclear reactors can enable. Some new reactors are designed to operate with smaller crews or even without active operative crews on-site, either entirely autonomous or remotely from a central location.

Having small or no on-site crews is essential, especially for very small units. If a high-enough level of safety can be designed and achieved without an active, on-site staff, it should be made possible through regulation and legislation. Not requiring any operator input diminishes the potential for human error, increasing safety and making it unnecessary to have additional systems to mitigate a potential human error.

Advanced Technologies

Many of the new advanced reactors under development aim for lower capital and operational costs through various means. Smaller capacity can rely on simpler passive emergency cooling instead of more complex and costly active cooling mechanisms. These also include non-water coolant that can enable lower pressures, decreasing the need for thick steel pressure vessels. Many designs also aim for higher temperatures, giving higher efficiencies for electricity production better suitability for high-temperature process steam production.

The potential for cost reduction seems significant, but it remains to be seen how much of those reductions can be realized. For example, changing the coolant from water to molten salt might introduce other costs or issues that current light-water reactors do not have. How these challenges are met and regulated will significantly impact the cost reductions.

Low-Cost Energy or Jobs?

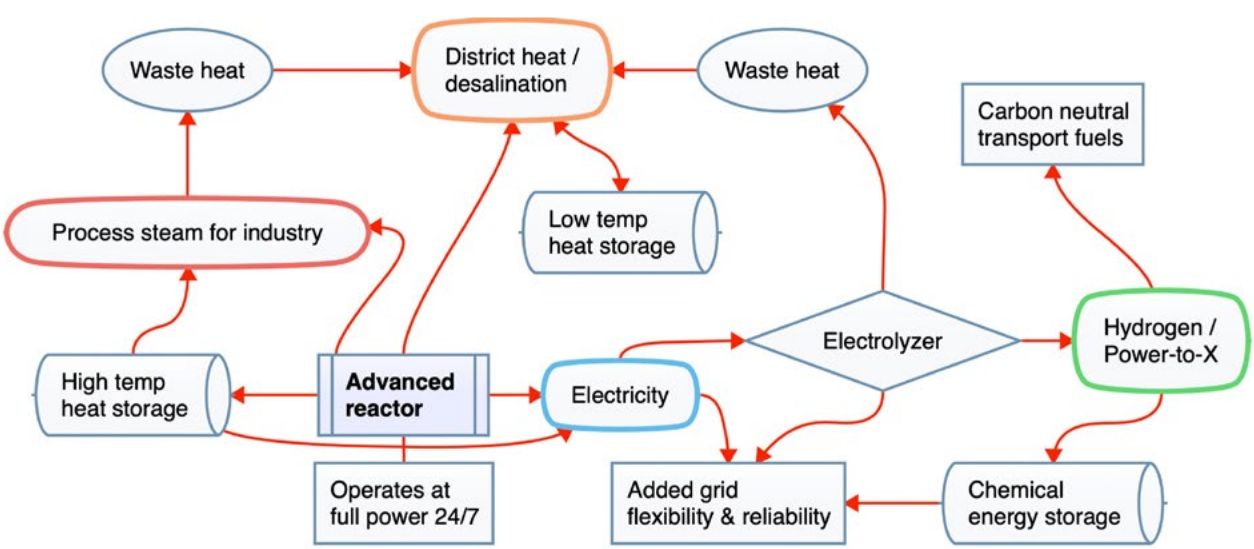
A primary sector like energy production aims to produce low-cost energy, not direct employment. The low cost of clean energy is essential for climate mitigation. Human labor is expensive, so we should aim for as few direct jobs in energy production as possible. The lower the cost of clean energy services, the faster we can displace fossil fuels. Lower cost for reliable energy increases productivity, and the average disposable income people will have to use in other ways, such as buying services. Clean, low-cost energy increases economic growth and jobs while decreasing emissions and other environmental harm. It also enables higher degrees of recycling of materials. And if energy prices are seen as too low in society, we can always increase them through taxation.

Production Profile (Co-generation of Multiple Products)

Many advanced reactors offer a more varied product portfolio from large power reactors that produce electricity. They have opportunities for co-generating different end-products at higher overall efficiencies.

The key strength here is that nuclear reactors produce reliable primary heat. This heat can be used to make steam for an electricity generator, but also for many other things we use heat for. These include industrial processes, high-temperature steam electrolysis, seawater desalination, and district heating. Heat can also be stored more easily than electricity in various ways, such as molten salts or firebricks for high temperatures or water and underground rock for lower temperatures (for district heating or desalination). A flexible nuclear reactor is a perfect heart of a multi-functional hybrid energy system.

Figure 9: An advanced nuclear reactor with local high-temperature heat storage can be a highly versatile part of a hybrid energy system. Image: Think Atom Ltd.



Potential for Scaling

In addition to the ever-so-important cost reduction potential, shipyards also offer a step-change in scaling up production. A recent study found that there is already significant opportunity in shipyard manufacturing, as due to tight global competition, many shipyards do not run anywhere near full capacity[24]. The world's shipyards produce between 1,500 and 3,500 ships per year while working at roughly 50% average capacity. Many of the vessels manufactured go to work in the fossil oil and gas exploration, extraction, and transportation industry. So there is both unused capacity and capacity that would be no longer needed if we started manufacturing FNPPs instead. In 2019, there were 281 active shipyards globally.

One of the advanced nuclear developers recently made a study regarding manufacturing their plants in a large Korean shipyard. While the cost estimates were very promising (not unlike the numbers presented in this study), the scale was also breathtaking. While the shipyard in question is enormous (around 5% of global capacity), it could manufacture some 40 ships with 500 MWe of reactor capacity per ship. That is 20 GWe of annual output capacity added, just from one large ship-

24 Missing Link to a Livable Climate, 2020, LucidCatalyst. https://www.lucidcatalyst.com/hydrogen-report

yard, without significant modifications, expansions, or investments needed for the shipyard itself.

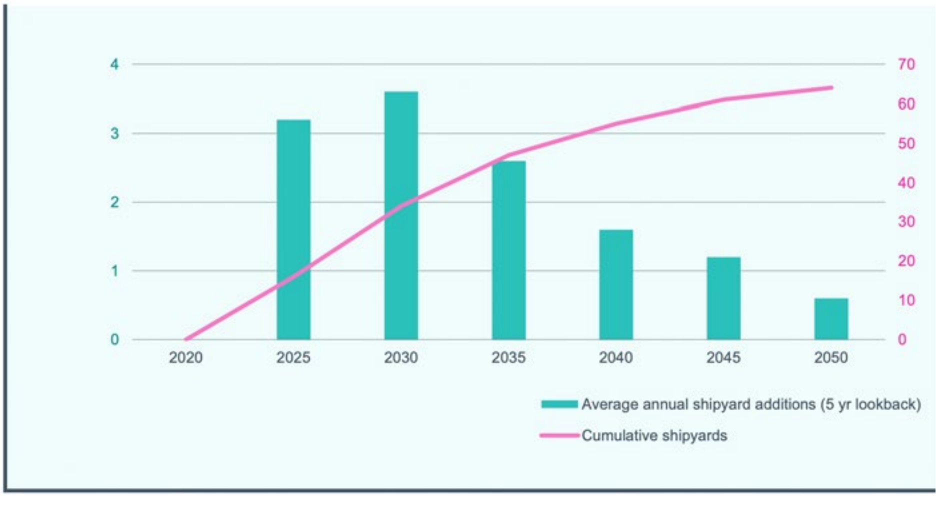
It would take only several dozen large shipyards to start shifting their production into these vessels to replace the estimated 2050 fossil fuels use with carbon-neutral e-fuels. Shipyard production can scale to the required level because it is already operating at a much higher one.

Scaling in Finland

The Finnish shipyard industry will be discussed later, but it is helpful to present some ballpark estimates here. Finland has three shipyards that could produce vessels in the 300-600 MWe capacity range, and some of these shipyards might be able to reach an output of multiple ships per year. This means that Finnish shipyards should have the capability to produce clean energy platforms on the gigawatt scale each year.

This is much faster than anything we have historically been able to do, even combining all types of energy projects under construction. In short, this is precisely the kind of step-change we need to respond to the scale of the climate challenge – and not just for Finland, as these power plants can be built in Finland and towed to other markets.

Figure 10: Globally, we need to start shifting a few new shipyards into producing these nuclear vessels per year by mid-decade. Image source: LucidCatalyst 2020



Floating Nuclear Power Plants, FNPP's

This chapter offers an overview and discussion on the various aspects of shipyard-built, floating nuclear power plants, FNPPs. There are still numerous unanswered questions, of which some are outlined and discussed here. This chapter is by no means exhaustive but hopes to offer some starting points for the many conversations we need to have.

Offshore, or Just Built in a Shipyard?

Shipyard manufacturing brings many benefits, and it enables much of the manufacturing cost savings, one of the big problems that nuclear construction currently has. But can we reap the cost benefits with shipyard manufacturing and site the power plants on land, or should we also go for offshore siting of floating NPPs, given that it might bring new issues? Both can be the "best" option depending on the situation and timeframe observed.

Like dedicated factories, shipyards can be good places to manufacture small nuclear reactors or modules, even if those reactors were placed on land. The difference to dedicated factories is that shipyards already exist, ready and capable, with much of the established supply chains and expertise available today. Building a new factory for this from the ground up requires significant up-front capital investment and trust in (or proof of) future sales.

The productivity and savings potential in shipyard manufacturing depends on the case. Even today, most of the components of large reactors are manufactured in factories, workshops, and shipyards, so this is not a new idea. If there is a need to manufacture complete reactor modules for on-land siting, then a capable shipyard might be an excellent location.

Another option is to manufacture the whole vessel at the shipyard and then tow it to a shoreline location and have it moored there, more or less permanently, or keep it afloat within a harbor near an industrial site such as a refinery, often located on the coast. This approach can still lower the overall costs due to more efficient serial manufacturing, less concrete and groundwork, potentially lower cost for the siting in general, and so forth. The Russian Akademic Lomonosov floating nuclear power barge is sited like this, with semi-permanent facilities built for it on the shore. It is still towable to another location as needed.

The "all-in" option is to design and manufacture vessels that will operate at sea, be it on national or international waters. While this brings some new requirements and problems, it also resolves many others. One of the significant issues is that having a reactor at sea also means that it is "Not-In-Anyone's-Backyard." Another is that it can be moved to another location as needed.

A nuclear reactor placed on a floating vessel at sea or near the shore will need to be designed for the purpose, just like on-land reactors are designed for on-land construction and operation. The different environment requires different design focus and new thinking from the regulator and the operator. For example, on land, reactors are usually built on a giant slab of concrete that will keep them stable in almost any circumstance. There will be no concrete slab on an offshore vessel, and it will be in more or less constant motion.

Light Water or Non-Water

Most of the global expertise in nuclear technology is within the water-cooled and water-moderated reactor technologies, or light-water reactors (LWR). While they are a prime candidate for FNPPs barges, they need to be (re)designed for that purpose. There are many marine reactors in operation today, but they are used for propulsion and often in the military, which circumvents some regulations for civilian power reactors.

The Russian Akademik Lomonosov has two KLT-40S reactors producing power and district heat. The KLT-40 was initially designed for ice breaker propulsion and was modified for this new use. The next step in Russia's marine reactor program is to modify the bigger next generation RITM-200 ice breaker reactor for energy production use. The key takeaway is that these reactors are already commercially available for offshore applications, and some are already in use. LWRs also have more readily available regulations, fuel supply, and expertise than more novel nuclear technologies.

On the other hand, non-water-cooled reactors can provide attractive benefits and cost-reduction opportunities compared to LWR reactors. They often require less active safety measures (and backups for them), have thinner and cheaper pressure vessels, simpler operations, etc. On the other hand, they might require new fuel types and produce new types of waste. And while this could be a benefit down the road, it is usually a hindrance in the short term, as we might lack both supply chains and regulations for these novel fuels.

The potential for cost reductions with these technologies is significant, including but not limited to higher temperatures which enable higher efficiency power production, and the significantly higher efficiency high-temperature steam electrolysis for hydrogen production.

Environmental Impacts

What are the environmental impacts of offshore nuclear? There are a couple of aspects to it, but they seem relatively small and often temporary. If the facilities are floating (although attached to the seabed with an anchor), there won't be much permanent environmental footprint left at the site. Compared to offshore wind, the impact might be similarly small, but on a much smaller area and without the potential impact for bird species that wind turbines have. There will be some amount of waste heat discharge, but that is a relatively minor issue at sea and gets quickly diluted. If the FNPP is sited in a harbor, the long-term environmental impact should not differ much from any similar industrial activity. A harbor is an industrial site that always has ecological impacts, but also offers benefits for people.

Material Requirements

The material requirements are relatively low even when compared to a land-based nuclear power plant, which already has the smallest materials footprint of any major energy source. Ships are comparably light structures, and little concrete, roads, or groundwork is needed with offshore siting. Steel production does have somewhat of a significant lifecycle emission, but this does not have a significant impact overall, especially compared to other energy production. If electricity is transferred to land by cables, these can be significant but recyclable. Less cabling will be needed compared to most offshore wind farms, as they span much larger areas.

Indeed, a recent environmental lifecycle analysis from

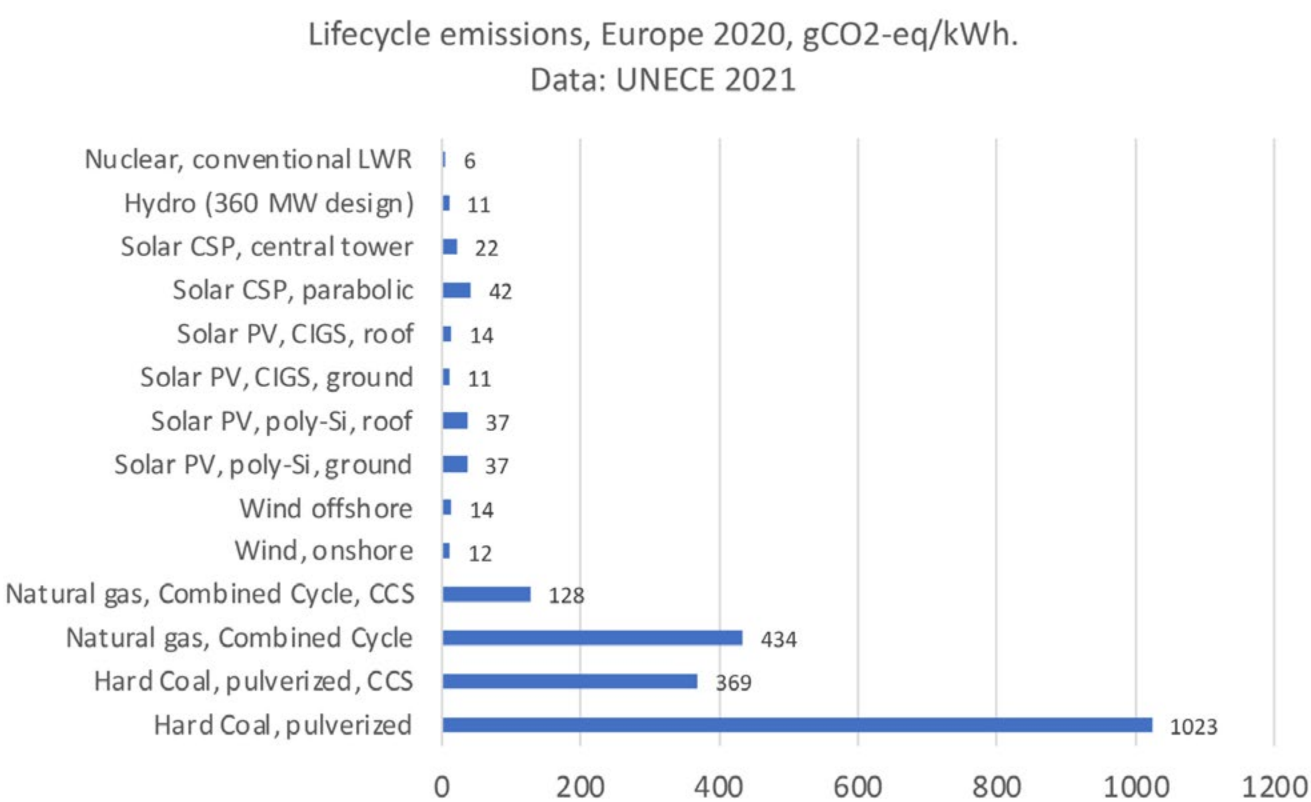


Figure 11: Lifecycle emissions of various energy sources in Europe in 2020. Data from UNECE 2021.

United Nations Economic Commission for Europe (UNECE) found that nuclear has the lowest average lifecycle emissions of all energy sources (Figure 11). It also has among the smallest environmental footprints in general.

Thermal Pollution

A nuclear reactor releases waste heat into its surroundings. If the power plant is near or at sea, it typically uses the sea as the heat sink. This means slightly warmer water near the power plant, but the overall impact is negligible. A helpful analogy is to think of a swimming pool full of water and someone dropping slightly warmer water into it with a pipette, one drop every now and then.

Thermal pollution can also be a valuable by-product if the FNPP is sited near or at harbors in colder climates. It can keep the nearby area free of strong and thick ice and lessen the need for icebreakers.

Uranium & Fuel Fabrication

Nuclear reactors use uranium (and, in the future, thorium) as their energy source, and this uranium needs to be acquired somehow. Currently, it is done mainly with mining or in-situ leaching. Due to uranium's extremely high energy density, mining needs are relatively small compared to other major clean energy sources (hydro, solar, wind). In the future, we can also extract uranium from seawater which has a small but constantly replenishing concentration of 3.3 parts per billion. Mainly this is a question of uranium prices and the costs of seawater extraction dropping with R&D efforts.

While uranium production might experience short-term bottlenecks, we are not running out of uranium, as there is plenty in the earth's crust and oceans. Another concern is fuel fabrication capacity, which might pose a bottleneck if a true "renaissance" of new nuclear comes online. In the medium to long term, we can build more capacity for fuel fabrication, and the same goes for uranium enrichment capacity.

Spent Fuel

When people talk about "nuclear waste," they often mean spent nuclear fuel. Spent nuclear fuel is exceptionally well-managed and has caused practically no harm to people or the environment in the 60+ year history we have had it. Politicians have not yet decided what to do with spent nuclear fuel over the long term in many countries. This causes anxiety, as people think this indecision is due to a lack of good solutions. That is not the case. There are multiple solutions to manage our spent fuel. Some of the more prominent include deep geological repositories and boreholes. These are regulated, designed, and built so they will not cause any significant harm to people or the environment, even at very long timescales. This is something that no other energy industry can claim, as their toxic and harmful waste does not have similar management in place. We can also reprocess, recycle, and reuse the spent fuel in current and future reactors to get even more energy out of it, reducing waste.

Finland is a forerunner in building a final repository, with the facility called Onkalo now under construction and the first batch of spent fuel going in around the mid-2020s. There is no reason to believe that such a facility, Onkalo or another one in a new location, could not be used to store spent fuel also from FNPPs safely, as long as this is accepted by the local community. Of course, suppose the spent fuel is different from current light-water reactors. In that case, further studies are needed to prove to the regulator and society that no significant harm will be done to people or the environment even during extremely long time scales. Spent fuel management is not a showstopper in any meaningful sense. However, it is one of the conditions to get a project included in the EU taxonomy of sustainable investments (more on that later).

Safety, Security, and Other Considerations

When people hear of floating nuclear power plants, the first thoughts might be: "What about storms and tsunamis? Pirates or terrorists? Military action?" While giving a conclusive answer to these concerns is not within the scope of this study, below is some discussion on various related matters.

Mobility as a Safety Asset

Nuclear reactors are designed with multiple layers of safety barriers. This means that, even in the case of a severe accident that leads to radiation leakage, the accident itself progresses relatively slowly. For example, even in the accident at Fukushima, with reactors designed in the 1960s and built in the 1970s, the accident took days to escalate to levels where radiation began to leak into the environment.

In Fukushima, it was challenging to move tens of thousands of people away from the accident zone due to the devastation from the earthquake and the following tsunami. The reverse would be the case with a floating facility. In a severe situation, the vessel can be towed to the open sea where it will not endanger people's health or the environment even if radiation gets released. Perhaps the need for an emergency preparedness zone (EPZ) can be viewed from a new perspective. Do we need a fixed EPZ if the vessel can be towed to another location instead of moving the people away?

Sink-Proof?

Can we be sure that an FNPP will not sink under any condition? Or, more precisely, how sure can we be, given that we only have a limited dataset on winds, storms, tsunamis, and such? And even more specifically, how can we prove this? Proving that "it can withstand a million-year wave" might be impossible simply due to the lack of data on such waves. To put it simply, we cannot know what we are trying to prove the design against, even if it might be possible to make a design that could be proven to be safe even in such a condition.

Perhaps we don't need to, as it might be easier to prove that even if something happened and a vessel sank, environmental and human harm would be insignificant. Perhaps they can even be designed so that the reactor can relatively easily be removed from the sunken vessel and recovered with a "strong hook and cable" if this is needed. Taking this to the next level, this can even be seen as an extreme-case safety barrier. In a severe and acute emergency, one can sink the vessel on purpose, as underwater, it will have ample cooling while even a couple of meters of water is enough to stop the strongest levels of radioactivity.

Even if such a reactor would need to remain on the deep ocean floor, it must be asked whether this poses an insurmountable risk of a significant negative environmental impact? Water stops radiation very effectively, and nuclear fuel is not easily dissolved in water. At the same time, the reactor will be effectively cooled by it, and the sediments will eventually cover the whole vessel.

Terrorists, Pirates, or Rogue-States?

The idea of terrorists or pirates taking over a floating nuclear power plant somewhere and using it for their nefarious purposes sounds like a perfect setting for a Tom Clancy thriller novel or a James Bond movie. But a more cool-headed analysis is also needed.

First, these are not self-propelled vessels as they need towing to move. Detaching them and preparing them to be towed would likely take days, not minutes or hours. Towing would be done at low speeds, as these vessels would be large and heavy.

Second, a floating NPP would be a hard target with an onboard security force and potential reinforcements nearby, either from local or international forces. Nuclear facilities are allowed to defend themselves with arms, so it would take a significant force even to attempt to take control of such a vessel. Such an approaching force would be easily seen by satellites and radars.

Third, one must question the perceived utility of such an effort. Even if a group could take over an FNPP somewhere, it would be questionable what they would hope to accomplish with it. Even the terror aspect seems relatively weak. The vessel would be out at sea, and any significant radiation release, if one would be managed despite all the designed countermeasures and short time frame available for such an effort, would likely pose a comparably small health hazard.

A Floating Dirty Bomb?

Here, the handy fact that such a barge would be ”mobile” also feeds the imagination with potential threats and scenarios and needs to be considered. Can these vessels be towed near a coastal city as a threat by some actor, state or non-state? That is indeed possible, at least in theory, but also something that might be extremely hard compared to the potential impact.

Many modern reactors are self-regulating and passively safe. It is extremely hard to get them to release any significant levels of radiation, let alone levels that would threaten the health of nearby populations.

If the actor were a nation-state, this would be a direct attack on another country, and a declaration of war, justifying a military response. No matter who the attacker would be, they would first need to gain control of the vessel. Then they would need to keep control of it, potentially for many days, despite the increasing presence of armed forces from the previous owner. They would also need to tow the vessel successfully in the presence of hostile armed forces who would have every incentive to see the towing boat not succeeding.

At the end of the day, such a vessel would not necessarily offer much value compared to the target's hardness. The most value would be in producing clean energy. This would not be something a terrorist group is interested in or even able to do, given that such a vessel is easily traceable and found by its owners. Further, the reactors are often designed to make it extremely hard to access the fuel. And even if one could, what then? Partially spent fuel from a civilian reactor is mainly useful for that single purpose: energy production in a nuclear reactor. It cannot be used to make nuclear weapons as such, not without sophisticated facilities. And if one possesses such facilities, one doesn't need spent fuel from civilian reactors to produce weapons-grade material in the first place.

One purpose of highly radioactive material such as spent fuel is to make dirty bombs. A dirty bomb is a device with a conventional explosive and radioactive material, and the explosive is designed to spread the radioactive material. Dirty bombs can be used to terrorize population centers. But given that radioactivity is extremely easy to detect and that we would very likely always have intimate knowledge of the whereabouts of such a vessel and the motivation to interfere, it would be tough to accomplish tasks like these.

Floating NPPs as Military Targets in a War

The Russian invasion of Ukraine has brought war to Europe's doorsteps. Combining nuclear power plants with warfare, missiles, and explosives is a scary and dangerous concept.

Power infrastructure, including power lines, power plants, and transformer stations, is critical during both war and peace times. If the national power grid goes down, our ability to operate decreases significantly. Hence, these assets need to be protected, especially during a war. As such, attacking nuclear power plants is a war crime, both on land and at sea. FNPPs out at sea can be towed to harbors for easier defense if the need arises.

On the other hand, having a well-protected, perhaps distributed, fleet of energy production facilities capable of producing synthetic fuels at scale is a valuable asset for energy independence and emergency preparedness. As of March 2022, both oil and gas in Finland are mostly imported from Russia.

International Maritime Regulations and Legislation

"The international legal framework currently does not prohibit innovative SMR projects. At the same time, the lack of international experience in the implementation of transportable SMR projects makes it impossible to create a detailed legal and regulatory framework, which is now in place for conventional high-power NPPs" - IAEA 2022

The international regulation of floating NPPs to operate worldwide is not complete for all cases and purposes. But, according to IAEA 2022 book on nuclear law[25]: "Expert consensus at the international level is encouragingly positive in terms of the prospects for the implementation of pilot floating SMR projects and shows interest in such projects at the international level." Indeed, as practical issues from an actual project often differ from more theoretical scenarios, pilot projects are likely essential case studies in developing the necessary legal framework and best practices.

An FNPP operating in a fixed position while connected to the grid by cables would be considered a nuclear facility. The state where the plant is operated (including territorial waters) would be responsible for the plant. In terms of liability, the position of INLEX is that transportation of floating SMR facility would be considered as transportation of nuclear material under the Vienna Convention.

25 https://www.iaea.org/newscenter/news/iaea-publishes-free-e-book-on-nuclear-law

INPRO[26] has been analyzing the legal and institutional aspects of transportable SMR projects since 2011, with a preliminary report published in 2013 and the second study due out in 2022. Finland is involved in the working group, and IAEA is establishing other relevant working groups, as this topic has gained international interest.

STUK would regulate an FNPP operated in Finland. It is another question who would supervise and regulate the design and manufacturing of FNPPs that would end up exported into other countries for use and whether there would be cooperation and sharing of work between national regulators. For example, if STUK would regulate one FNPP for Finnish use from start to finish, how much of their work would be applicable and transferrable into exporting the same design to another country, like Poland or Netherlands, and with what conditions? Or would the whole regulatory workstream be needed for each and every new operative country?

Indeed, a significant part of this opportunity is not dependent on operating or having Finnish ownership of the floating NPPs, nor Finnish regulations and legislation for such activity. Shipyards could act as contractors and subcontractors for non-Finnish actors wanting to own and operate such vessels outside Finnish waters. Yet without domestic, commercial experience to show, such customers would be much harder to get. To unlock the export market, a lot depends on Finnish politicians and officials allowing and supporting first-of-a-kind projects and domestic industry investments.

Potential Other Benefits of FNPPs

In addition to the potential for cost reduction and massive scalability, there are other benefits to floating energy plants. One of the clear benefits of an offshore facility is that it is not in anyone's immediate "backyard," and it doesn't require land to be used, which always has

26 International Project on Innovative Nuclear Reactors and Fuel Cycles

alternative uses. This can offer much less NIMBY opposition than regular, on-land installations and infrastructure, which is already slowing down the transition to clean energy.

Mobility as an Asset

One of the risks of significant, long-term investments is the potential shift in local/national politics and policies (political risk) and the development of markets (market risk). These risks are considerable for large, up-front, long-term investments like nuclear power plants. They also significantly increase the financing cost, which is especially harmful to large, up-front, long-term investments like nuclear.

In recent years and decades, one only needs to look at Germany, Belgium, and Sweden to see the political risk play out. These countries have seen valuable assets shut down prematurely or made economically infeasible to run by additional taxes.

But if the power plant is much more rapidly deployable (shorter time from decision to plant operating) and can be towed to another location if the market or the political situation deteriorates too much, these risks are greatly diminished. This mitigates these risks both for the investor/owner and the financier, lowering the cost of capital. This, in turn, means even lower costs for the end-product, increasing its competitiveness and ability to replace fossil fuels sooner and faster.

Increased Emergency Preparedness

One significant benefit of FNPPs is the added security of supply for power grids in case of blackouts and grids failing. These problems can occur due to many different factors from human-caused (decreasing reliability of grids due to mismanagement, lack of preparation for fluctuations of variable energy sources, sabotage, etc.) to factors out of our immediate control (solar storms, earthquakes, tsunamis, and other natural disasters and extreme weather events). An offshore barge producing fuels can be separate from the main power grids on land, and therefore they can survive such events more readily. Bringing the power grid back online as fast as possible – a crucial thing given our total reliance on constantly available electricity throughout our society – would greatly benefit from this kind of external and mobile source of significant and reliable power and voltage output.

Many experts say that power grid failures, even catastrophic ones, are more a question of "when" rather than "if," yet preparations for such an event have not been sufficient. To have ships that can be towed to any coastal crisis zone in a matter of days or a couple of weeks would make a big difference in answering these local crises at a regional or even global level. For a country, having such vessels nearby would give the national emergency supply agencies and other emergency planners an additional layer of peace of mind. They would know that there is another independent way to bring a failed electricity grid back up on short notice.

Another benefit for emergencies is the increased energy independence and self-sufficiency for multiple energy products (power, fuels, other chemicals) these types of multi-purpose energy vessels would bring, especially for countries that depend on imports of crucial energy products such as liquid and gaseous fuels and electricity. Domestic hydrogen production, which can be further used to produce liquid and gaseous fuels for critical infrastructure and ammonia for the fertilizer industry, significantly benefits countries' emergency preparedness.[27]

Analyzing the implications for literally any country becoming able to produce their critical fuels at a reasonable cost instead of relying on the handful of countries producing most of the global oil and gas output is out-

27 At the time of writing, nitrogen fertilizers, which are currently made from hydrogen taken from natural gas, are seeing an availability crisis in some European countries as prices have increased to levels that many farmers can't afford.

side the scope of this report. Indeed, these implications are so enormous from so many perspectives that they would deserve a book of their own.

The energy markets often do not recognize these benefits and added value in their daily price-finding. Still, they can be accounted for through other means, perhaps as a part of a nation's emergency preparedness plans and budgets. It must be noted that towing these barges might be an activity that requires excessive permitting and preparations in normal conditions. It would be prudent to write laws and regulations so that moving them to a new location in an evident crisis can be done on short notice, with permission from the government, a relevant minister, or some other suitable actor.

Potential Offshore Reactor Vendors

While the idea of a nuclear-powered ship is still foreign to many, the industry has a long history, especially in military vessels (submarines and aircraft carriers) and in Russian icebreakers built even in Finland. In addition to these, the scene now has several developers and vendors, big and small, designing their reactors especially for marine use, either for propulsion or energy production.

Core Power – Propulsion for Commercial shipping

The UK-based Core Power develops the m-MSR with Terra Power, Southern Company, Orano, and 3M. It is a marine iteration of the Molten Chloride Fast Reactor (MCFR) by TerraPower.[28] They envisage it used for direct propulsion of large vessels and the production of electricity and clean synthetic fuels. TerraPower recently announced it would build its Natrium demonstration reactor at a retiring coal plant in Wyoming, with nearly $2 billion of support from the U.S. Department of Energy.[29]

Core Power focuses on the marine sector. The transition stage will, according to them, see fossil heavy oil and LNG used in small and medium ships replaced with clean fuels, ammonia or methanol, produced at terrestrial or floating refinery plants powered by advanced nuclear reactors. Core Power envisages that the next generation of large ships will have small nuclear reactors (such as their m-MSR) providing power and propulsion for the ship. This would bring significant advantages. Nuclear-powered ships would not need refueling, could move much faster than ships today, and could deliver power to ports when loading and offloading cargo, which would be especially useful at remote sites.

Seaborg – Molten Salt Reactors from Denmark

Seaborg Technologies develops a 100 MWe Compact Molten Salt Reactor (CMSR) designed for a floating barge. They have four different standard sizes for the barges, fitting 2, 4, 6, or 8 CMSRs and offering 200-800 MWe of capacity. The reactors operate for 12 years without refueling, and there is one extra slot for each reactor in the power barge design. After the first reactor has run for 12 years, a new reactor is installed in the empty slot and started up. After 24 years, the whole barge with the reactors is brought to a central facility for decommissioning.

Seaborg is currently planning to build its power barges in South Korea, and its initial market is the South-East Asia region. They have publicly stated a goal of producing 200 Power Barges per year by 2035. If all of those would be the 200 MWe "base model," this would add 40 GW of clean capacity per year, around 10% of the current global nuclear fleet. In 2022 April, Seaborg and Samsung Heavy Industries (shipbuilding) announced a partnership for building floating NPP's for multiple energy products[30].

28 https://corepower.energy/
29 https://www.energy.gov/ne/articles/next-gen-nuclear-plant-and-jobs-are-coming-wyoming
30 https://www.world-nuclear-news.org/Articles/Samsung,-Seaborg-partnership-on-floating-nuclear-r

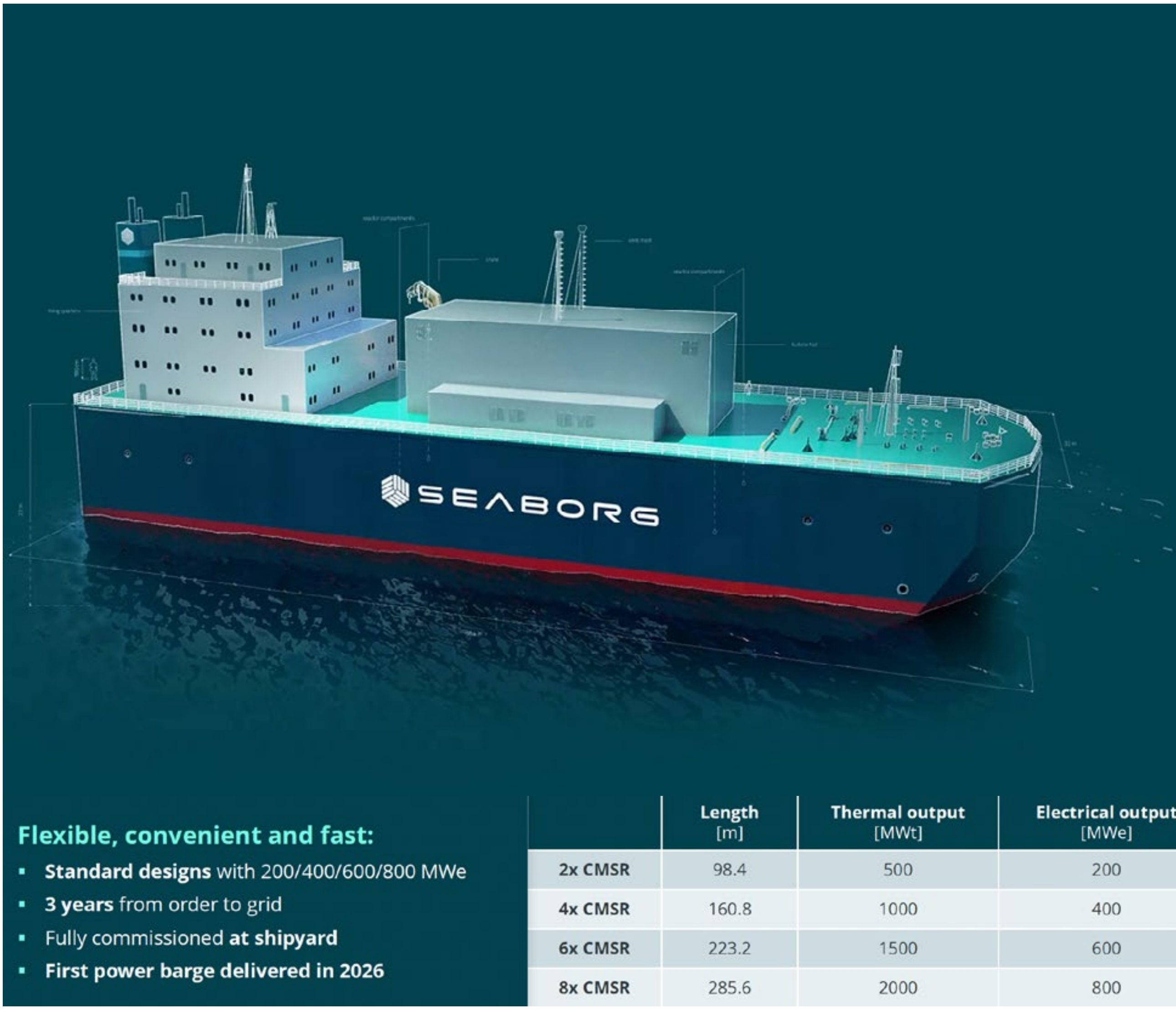


Figure 12: Image Credit: Seaborg Technologies

ThorCon – Molten salt

ThorCon has somewhat of an unorthodox approach[31]. They aim to scale up the Molten Salt Reactor Experiment (MSRE) technology, which operated for four years at the Oak Ridge National Laboratory from 1965 to 1969. In this sense, ThorCon requires no new technology. It uses technology already tested to work, only scaling it up to commercial scale into a pilot plant and using it to verify the design further. As a result, the core of the ThorCon needs to be changed every four years, but on the other hand, it doesn't require specialized steels and alloys for the structure, lowering cost.

ThorCon is operating mainly in the South-East Asia region. In 2019, the Indonesian Ministry of Energy completed a study on the safety, economics, and grid impact of having a 500 MWe ThorCon prototype. Their project in Indonesia has two phases: 1. Build and test a 500 MWe prototype ThorCon to get an approved license for future power plants. Phase 2 includes shipyard-manufacturing 3 GWe more of ThorCon reactors for the Indonesian power utility to provide low-cost and low-carbon electricity for the nation's grid. ThorCon targets a 3 cents/kWh cost for electricity.

31 https://thorconpower.com/

Rosatom – The Nuclear Giant that Does Everything

Rosatom has built more than 20 small reactors for civil marine applications and has about 400 reactor-years of operational experience with their nuclear icebreakers. Rosatom already has one floating power barge in operation, the Akademic Lomonosov, which has two KLT-40 -based reactors.

Rosatom is now designing the improved version, which has two of the more powerful, more compact RITM-200M reactors in it. RITM-200m is a 190 MWt, 3+ generation pressurized water reactor with land-based and floating designs. It has a fuel cycle of 10 years and a design life of 60 years, with commissioning planned for 2027 or 2028. This FNPP will be significantly smaller yet has 30% more electrical capacity than the Akademik Lomonosov.

Rosatom has ambitions to provide turnkey, full-service contracts for interested customers worldwide. The customer gets the energy delivered, and after that, the FNPP is towed back to Rosatom for spent fuel management, reloading, maintenance, and eventual dismantling. Since the recent Russian military invasion of Ukraine, the opportunities for Rosatom to export its products and services have shrunken significantly. It remains to be seen how long this situation persists.

GE Hitachi

GE Hitachi's BWRX-300 reactor is designed to be sited on land. Given the compactness of the design and the similarities in design philosophy to what would be used on an FNPP, it could be redesigned as an FNPP, according to some of their senior design team members[32].

The Canadian utility OPG selected the BWRX-300 to be built at their Darlington site. Multiple European countries, including Poland, Sweden, and Estonia, have expressed serious interest in the design. It is now likely that the BWRX-300 will be built in multiple units starting in the 2020s.

32 Based on an interview I had with them.

One of the main issues for siting the BWRX-300 on a vessel is the height of the power plant. This is non-negotiable in this type of reactor due to the length of fuel elements and certain height needed for natural cooling circulation. The total height of the system is roughly 60 to 65 meters. Still, if the height requirement can be met, the design itself could be modified to be fitted on a floating vessel or platform. The team estimates this work to take between 6 and 18 months and requires a multi-disciplinary team of roughly half a dozen experts, give or take a few, and some experts from the shipyard side. Given enough interest from a credible party, the team at GE Hitachi might well be open to doing such a redesign.

The BWRX-300 would represent a low-hanging fruit as far as reactor technologies go. Among the light water SMR designs, it is among the most mature. Most other options are molten salt-based, and while these reactors might be easier (from a dimensions perspective) to be designed as a module in a floating vessel, they have other obstacles and bottlenecks. These include less experience and lower technology readiness level, no similarly available supply chain existing for fuel, lack of regulators, and less experience of the technology within regulators.

NuScale Power

NuScale Power has been working with Prodigy Clean Energy[33] (a Canadian company specializing in designing and developing marine nuclear power plants) since 2018 to investigate the feasibility of integrating a NuScale design onto a marine platform to be fabricated at a shipyard. In 2021, their cooperation took another step with another Memorandum of Understanding[34]

33 https://www.prodigy.energy
34 https://newsroom.nuscalepower.com/press-releases/news-details/2021/NuScale-and-Prodigy-Sign-Memorandum-of-Understanding-to-Support-Business-Development-for-a-Marine-Deployed-Nuclear-Generating-Station-Powered-by-the-NuScale-Small-Modular-Reactor/default.aspx

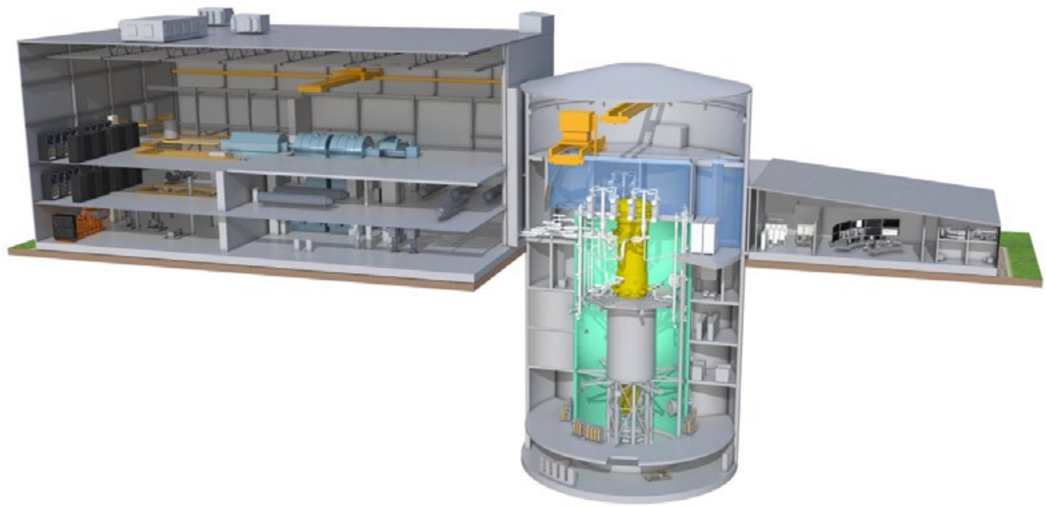


Figure 13: The BWRX-300 power plant. Image credit: GE Hitachi

(MoU), deepening their collaboration. The purpose is to offer capacities from 100 MWe to 900 MWe, depending on customer needs. NuScale offers a 4-pack, a 6-pack, and a 12-pack of their 77 MWe (250 MWt) integrated reactors.

Their design is meant to be towed near shore, moored there in a protected setting, and then connected to the on-land grid. While there is no public information yet on potential customers or sites, the target is to have the marine power plants ready for power generation before 2030.

KEPCO Power Barges

In 2020, the South Korean KEPCO signed an MoU with Daewoo Shipbuilding & Marine Engineering (DSME) to cooperate on developing FNPPs[35]. They are developing an FNPP equipped with the BANDI-60 reactor(s), a 60 MWe pressurized water reactor.

35 https://www.world-nuclear-news.org/Articles/Kepco-E-C-teams-up-with-shipbuilder-for-floating-r

China – CNNC & CGN

Two of the Chinese nuclear giants, China National Nuclear Company and China General Nuclear Power Corporation, have been developing marine versions of their reactors (ACP100S and ACPR50S, respectively) since 2016[36].

Synergetic and Kärnfull Next

In recent months, at least two nuclear project development companies have emerged that include shipyard manufactured FNPPs in their portfolios. These are Synergetic (UK/US) and Kärnfull Next (Sweden). Kärnfull is currently collaborating with GE Hitachi to deploy BWRX-300 reactors for on-land development[37], but also mentions the possibility for floating NPPs. Working with their South Korean supply chain partners, they are also interested in partnering with any local, in-country suppliers and manufactures to enhance local content.

36 https://www.globalconstructionreview.com/china-develop-fleet-floa7ting-nucl7ear-p7ower/

37 https://www.powerengineeringint.com/nuclear/karnfull-next-and-ge-hitachi-partner-on-swedish-smr-roll-out/

Synergetic is more focused on shipyard built floating nuclear power plants and offering competitive hydrogen production through new technologies like high-temperature steam electrolysis. They are technology-agnostic as far as the heat-source goes, and plan to work with reactor vendors appropriate for the target country and the customer needs and requirements. Recently, Synergetic and Kärnfull Next announced a partnership.

Case Finland – Capabilities and Stakeholders

Finland is a small country. But for such a small country, we have a lot of the necessary pieces of the puzzle. We have nuclear industry and operators, world-leading waste management, reputable and trusted regulator, capable shipyards interested in new opportunities, high public and political acceptance for nuclear energy, and legislation and regulatory reform on its way, which also considers new types and uses of nuclear power.

What we do not have, we can find international partners for. These might include the development and manufacturing of the core reactor systems themselves and some parts of the nuclear fuel cycle such as uranium enrichment (and, to a degree, mining) and fuel fabrication.

There are multiple ways of managing this. The reactor system can be manufactured somewhere else and brought to the shipyard for installation. We can also tow the vessel to another location for reactor installment (like we did with the Russian icebreakers built at the Helsinki shipyard). Fuel can be loaded, and necessary tests done either in Finland or at some other location the vessel is towed to.

Capabilities can also be developed and increased as experience is gathered, allowing us to reap a larger share of the value chain over time. Below is a brief overview of the relevant Finnish actors and stakeholders.

Nuclear Industry

Finland has two major nuclear license holders, Fortum and TVO, and Fennovoima is preparing to be one, although it remains to be seen what their future will show. Fortum is a publicly-traded multi-national utility with significant ownership from the Finnish state. Fortum has various energy assets in its portfolio, from coal to gas to nuclear, hydro, and other renewables.

TVO is a non-profit cooperative (a Mankala-company) that is currently purely a nuclear operator. They operate the Olkiluoto nuclear power station, which has three reactors. TVO is owned by energy-intensive industries and utilities, to which it sells the electricity it produces at cost.

Fennovoima is also a non-profit cooperative (Mankala). With the Russian Rosatom as a significant owner and technology provider, their project encountered problems when Russia attacked Ukraine. At the time of writing, it is still unclear what will happen.

Fortum has already expressed interest in becoming an owner or operator for small reactors producing heat for local users if the local utility is too small or otherwise unwilling to take on the full responsibilities of becoming a licensed nuclear operator. It is not far-fetched to think that Fortum might also be interested in owning or operating floating nuclear power plants and producing clean energy products such as electricity, hydrogen, or ammonia for customers with long-term purchasing contracts. Creating a Mankala-type entity for this purpose is also a possibility and would share the risk and the need for capital/collateral between more companies. As a Mankala-company, TVO and its owners might also be interested in this kind of activity.

Helen, the district heating and power utility owned by Helsinki, has recently shown significant interest in nuclear operations, especially regarding providing clean, reliable, and low-cost heat for their district heating network with small reactors. Whether they aim to become a licensed nuclear operator or team up with one of the existing license holders remains to be seen. Other larger coastal cities with more extensive district heating networks include Vantaa, Espoo, Turku, and Oulu.[38]

Finland also has organizations and business ecosystems for parties interested in nuclear and SMR projects. These include FinNuclear and ecoSMR[39].

Skilled Professionals

One critical issue would be the availability of skilled professionals in the wider nuclear sector. Steps should be taken to ensure more people are available and interested to work in the many tasks involved. The nuclear field includes many professions outside nuclear plant operations, such as construction and manufacturing, regulation, legislation, finance, quality control, logistics, supply chain management, communications, etc. Many of the "nuclear industry" professions are the same as those in other industries, but with the added training to deal with nuclear-related issues. This training should be made available to mitigate bottlenecks.

There will also be a growing need for more R&D in the fields involved. Hydrogen production with electrolysis at a large scale and synthetic fuels production are existing industrial activities. Still, they would need to scale up significantly and involve the nuclear sector and all the regulations and responsibilities that come with it. Training skilled professionals takes multiple years, so foresight is needed.

38 See more detailed analysis of the Finnish district heating network from "Nuclear District Heating in Finland" -study here: https://thinkatomnet.files.wordpress.com/2019/04/nuclear-district-heating-in-finland_1-2_web.pdf
39 https://finnuclear.fi/ and https://www.ecosmr.fi/

Shipyard Industry

"From a technological and expertise perspective, we can start designing and constructing these types of vessels today. The main obstacles are political and public support and acceptance and availability of initial funding." – Finnish shipyard industry insider

One of the key motivations for this study was the fact that Finland has a long tradition in the maritime and shipyard industry. The marine industry includes 3,000 companies from many sectors, including ship owners, ports, designers, software and system providers, maritime equipment manufacturers, and shipyards. It employs 50,000 people and has annual revenues of 14 billion euros. This means that much of the needed expertise, licenses, procedures, supply chains, and infrastructure are already in place for this new type of new product. The potential value of this asset is hard to overstate.

Finnish shipyards have been building enormous oil platforms, icebreakers, and cruise ships for over 40 years. In 2021, Finland had ten shipyards[40]. These are:

- Meyer Turku
- Helsinki Shipyard
- Rauma Marine Constructions
- Pori Offshore Constructions (recently bought by Enersense)
- Turku Repair Yard in Naantali
- Uki Workboat in Uusikaupunki
- Western Shipyard in Teijo
- Laitaatsilta Shipyard in Savonlinna
- Suomenlinna Shipyard
- Suomenlahti Shipyard

40 https://meriteollisuus.teknologiateollisuus.fi/en/marine-industry-finland

Of these, the first four are the most prominent or most capable in the context of this study, even though the Finnish maritime sector is deeply networked within and with other European actors. Each of them has at least some relevant expertise, as none of the Finnish shipyards can be considered "bulk" but more of a specialized shipbuilder. This chapter is based on publicly available information and interviews with representatives from the shipyard industry.

For decades, the maritime industry has built and operated high-quality equipment and constructs that work safely in extreme conditions worldwide, from icebreakers to oil- and gas drilling platforms. From a quality assurance point of view, this industry is already quite comparable to the nuclear industry. Still, it has managed to also reduce costs significantly through standardization and smart, highly productive manufacturing. The nuclear industry could dramatically benefit by taking some of the lessons available here and applying them to regulation, legislation, manufacturing, and operations. One way to do that is through closer cooperation and taking the construction process to the shipyards.

Below are short introductions to the leading shipyards interviewed for this study. Each of them saw the opportunity as highly interesting and worthwhile for further investigation. The main risks and bottlenecks seen were political license, public acceptance, and initial funding. These are all things that have been rapidly improving in Finland for several years. European Joint Research Centers report recently concluded that nuclear is as sustainable as any other activity already included in the EU Taxonomy for sustainable investments. The inclusion of nuclear power in the taxonomy is now looking quite likely[41], so the opportunity to get public funding for the initial stages has significantly improved. Indeed, this is especially the case in Finland, where we already have the final repository of spent nuclear fuel under construction.

41 European Commission released their Complementary Delegated Act which includes nuclear, in early 2022 and the European Council and European Parliament should vote on it by summer of 2022.

Meyer Turku

Meyer Turku[42] specializes in highly complex cruise ships, car-passenger ferries, and special vessels and is one of the leading European shipbuilding companies. The shipyard employs 1,800 professionals and is owned by the Meyer family, which also owns two other shipyards in Germany. Their grading dock is 365 meters long and 80 meters wide, and they recently built the 337 meters long cruise ship Costa Toscana. Size-wise, Turku has by far the largest capacity.

Helsinki Shipyard

Helsinki Shipyard[43] specializes in special vessels for demanding conditions and routes, such as icebreakers and other ships used in arctic conditions, including nuclear-powered icebreakers, although the reactor installations were done elsewhere. Algador Holdings acquired it in 2019, but shipbuilding has been at the site for over 150 years. It employs roughly 400 professionals and has 280 meters long and 34 meters wide covered grading dock.

As per my interview, the Helsinki Shipyard would be interested in being involved and building FNPPs. They see the overall potential and feasibility certainly worth inspecting more closely. Public and political acceptance was seen as critical, both for the shipyard itself and its network of suppliers and subcontractors. Serial production would bring costs down and enable long-term investments in personnel expertise and the shipyard's capabilities.

The current owners are from Russia, so the shipyard's future is somewhat unclear.

42 https://www.meyerturku.fi/
43 https://helsinkishipyard.fi

Pori Offshore Constructions

Pori Offshore Constructions (POC[44]) has experience in offshore oil- and gas exploration & production, offshore wind projects, and large pressure vessels, and special steel constructs, including for power plants and nuclear projects. Only a few know that the Mäntyluoto Shipyard[45] near Pori was initially built by the Finnish industrial corporation Rauma-Repola to help Finland build a dozen or so nuclear reactors planned to be built after Loviisa 1 and 2 and Olkiluoto 1 and 2. As those plans were eventually canceled, the shipyard went to look for business aboard. After an extensive sales trip to Russia, it became clear that there was no business in nuclear construction. The company quickly pivoted into making offshore oil and gas drilling rigs – another extremely demanding, tightly regulated, quality-conscious market.

Enersense International Oyj recently acquired Pori Offshore Constructions (POC). POC has an impressive list of quality certificates and licenses even for nuclear components, and they did deliver some into Olkiluoto 3, for example. As per my interview with key people at Enersense and POC, they are highly capable and interested in both designing and constructing nuclear-related components, modules, and vessels, as they see nuclear energy as an essential part of the clean energy transition. Enersense is already involved in the clean energy sector through their offshore wind projects.

Rauma Marine Constructions

RMC[46] employs roughly 200 professionals and operates within an extensive network of partners. It is the only large shipyard in Finland with Finnish ownership. RMC has built demanding vessels like multi-purpose icebreakers, car- and passenger ferries, and large patrol and combat vessels for the Finnish Navy. The shipyard can build ships ~240 meters long and 85 meters wide or simultaneously have two narrow ships under work. They are well-networked with the maritime industry in Finland and Europe and often acquire modules from the nearby Pori Offshore Construction -shipyard for assembly.

As are the others, the RMC interviewee seemed very interested in looking more carefully into the opportunity to build and assemble FNPPs in Finland. Securing public and political acceptance was seen as essential, as well as finding funding for the initial feasibility and design work. Other comments included speculation on whether it would make sense to do parts of the project somewhere else (such as reactor installation, initial fueling, cold and hot systems testing) or manage them in Finland. Systems testing can take 3 to 6 months, even with a regular ship.

Deployment Models

Depending on the level of ambition and vertical integration, the manufacturing and deployment of FNPPs in Finnish shipyards can manifest in several ways. Subcontracting components, modules, design services and such for some other shipyards that do the main assembly would be one commonly used practice – whether the assembly shipyard is another one in Finland or somewhere else. For example, Pori Offshore Construction has the licenses and certificates needed for demanding nuclear grade component manufacturing, which it could supply for vessels that have their hulls and other systems assembled at other Finnish shipyards. Another example of this is the nuclear-powered icebreakers made at Helsinki Shipyards, which were transported to St. Petersburg to install the reactor systems.

Further, it is another level of involvement to load the fuel and make the necessary nuclear systems tests. Whether that should or would happen in Finland or somewhere else is a case not in the scope of this study, but certainly something we need to have a deep, open

44 https://www.porioc.com
45 Some prefer to not call it a "shipyard" but rather a machine shop with a pier. For brevity, this document will refer to it as a shipyard.
46 https://rmcfinland.fi

discussion about. If we offer a vertically integrated "turnkey, cradle to grave" service like what Rosatom has been offering to its customers worldwide, we would be responsible for fuel loading, decommissioning, and managing the spent fuel.

This is an entirely different proposition than the Russian icebreakers, where we "only" built the ships themselves, with reactors installed elsewhere. The amount of value that can be captured and the market's potential size would be significantly larger with the "full service" solution – even if we would subcontract many of the systems, including the reactors/reactor designs themselves from other parties.

It is a fact that Finland is currently the leading western country that has managed to both make the political decision and is now building the final disposal of spent fuel. From the broader environmental and safety point of view, it would be beneficial for us to sell the solution to others that have not yet managed to solve the related issues. The less we have waste repositories, the safer, environmentally benign, and more cost-effective the overall solution is.

We also know and have ensured through strict regulation and transparent operations that constructing a final repository for spent fuel has a **comparably tiny environmental footprint and has practically zero risk for public health today and even at very long timescales**. If applied, this knowledge is very valuable both for the environment and the economic well-being of both Finns and people in other nations.

Summary of Shipyard Industry

Multiple shipyards in Finland are both willing and capable of starting designing and then manufacturing FNPP type projects in the coming years. It is likely that each shipyard, as they have different capabilities and facilities, would likely have a design of their own, even though the differences might be more related to the vessel instead of the nuclear power module itself.

The size of the grading dock at the shipyard also sets the limit for the size of the vessel. Helsinki has a narrower grading dock (34 m) than Turku and Rauma, which both have docks 80+ meters wide. They can build barges twice as wide as Helsinki or build two narrower vessels simultaneously. From a size perspective, one could say they have roughly double the capacity of Helsinki, with Turku also having a significantly longer grading dock than both Rauma and Helsinki.

Table 2: Physical parameters of Helsinki, Turku, and Rauma shipyards

	Length, m	Width, m	Covered?
Helsinki	280	34	Yes
Turku	365	80	No
Rauma	240	85	No

To find the long-term maximum output rate from the current facilities, we can make the following assumptions. In the longer term, shipyards can move to a "two vessels per year" cycle of releasing new vessels, especially if they are manufacturing the same design in series. Helsinki would have an output of two (smaller) ships per year, and both Turku and Rauma would have an output of either two larger vessels or four smaller vessels each.

Later in this study, three potential designs are presented, two at 1,2GWe total capacity and one with 600 MWe. The smaller one would be fit to be built in Turku and Rauma but too wide for Helsinki. Here we assume that a smaller design that would fit at the Helsinki shipyard would have half the capacity, at 300 MWe. Turku and Rauma would be able to build either twice the number of smaller ships or the same number of ships but with double the power capacity.

In megawatts delivered per year, the maximum capacity with these assumptions would be:

- 600 MWe / year in Helsinki
- 1,200 MWe / year in Turku
- 1,200 MWe / year in Rauma

The total capacity addition per year would be 3,000 MWe, almost twice the recently commissioned Olkiluoto 3's capacity. The shipyard industry operates as a network, so the work would be spread throughout the supply chain. Pori Offshore Construction might focus on delivering the nuclear-grade components and modules, as they have many necessary licenses and certificates. The reactor systems themselves might be built at a factory and shipped to the shipyard for installation, or the vessels transported to another location for reactor installation.

These assumptions are just educated guesses and need to be taken with a grain of salt. This is also a somewhat theoretical calculation, but it does give us the "maximum output capacity" of the shipyard industry. The shipyards have other critical projects, such as supplying the Finnish navy and border guard with specialized vessels. On the other hand, our calculation is not assuming any significant new investments from the shipyards into expanding capacity.

Further details, the potential capacity of the shipyards, and the power capacity of the vessels would depend on the detailed design of the ship, the reactor chosen, and the other systems on the ship. But it would not be outlandish to assume that the Finnish shipyards could deliver between 1,000 to 2,000 MWe of capacity per year in total while still producing other vessels for other uses.

Assuming this "half of maximum capacity," adding 1,500 MWe of reliable, clean capacity per year would be a complete game-changer for Finland and would make a significant impact even in the European context. This capacity would deliver some 12 TWh of clean electricity per year.

If the vessels had an operational lifetime of 30 years, the total fleet we could build and then maintain from our shipyards would produce 360 TWh of electricity per year. If that electricity had an average selling price of 50 €/MWh, the fleet would deliver 18 B€ in revenue per year.

(Petro)chemical Industry

Finland has a significant chemical industry, mainly dealing with petrochemicals (oil, gas, and other petrochemicals refining) and biofuels. Other sectors include medical drugs, plastics, rubber, cosmetics, cleaning chemicals, and the paint industry. The chemical industry revenue is around 24 billion euros, of which roughly half is exported, and it is the second-largest export industry in Finland, right after the forest industry. The sector employs directly and indirectly nearly 100,000 Finns, and annual investments are roughly 1.3 B€.

The main actors in fuels and biofuels are Neste Oil and St1, as well as UPM. These companies should be interested in significant amounts of clean, low-cost hydrogen for their processes and as a feedstock for e-fuels and enhanced biofuels.

Case Kilpilahti

Neste Oyj refinery in Porvoo, Kilpilahti, is Finland's largest user of hydrogen by a wide margin. It uses roughly 3,000 GWh of hydrogen (over 100,000 tons) per year and makes it mainly from natural gas and refinery gases with steam reforming. This releases 1.2 Mtons of Finland's total emissions, while the whole refinery emits 2.7 Mtons of CO_2, roughly 5% of Finland's total emissions.

One FNPP with a 500 MWe reactor would be sufficient to produce the needed hydrogen without emissions. Depending on the configuration, the vessel could also provide the process steam and electricity required for the refining. In the future, the crude oil now used as feedstock for refined products such as jet fuel, gasoline, and diesel needs to be phased out. If it is replaced with clean hydrogen and bio-based carbon or nitrogen, the demand for clean hydrogen could grow orders of magnitude.

In a recent piece of the Finnish business-magazine Talouselämä, the numbers were laid bare[47]. Today, the Kilpilahti refinery, owned by Neste, uses 130 megawatts of electricity in its processes that refine 12.5 million tons of fuel per year. While the company says it is a firm believer in clean hydrogen, scaling production up enough to use the hydrogen as raw material for e-fuels is a daunting task. Producing just one million tons (8% of the current output) of e-fuels would use 3 GWe of electricity, a Neste representative said. Extrapolating from there, producing 12.5 million tons of e-fuels would require 37,5 GWe of constant 24/7 electricity production. This equals 75 FNPP ships with a 500 MWe reactor each. However, this might be a significant underestimation, or would require other significant inputs as well. 3 GW of constant electricity can produce roughly half a million ton of hydrogen per year, assuming 70% electrolyser efficiency.

Regulators, Legislators, and Policymakers

"These types of floating nuclear plants could be a good fit for Finland" – Senior Ministry official

While the concept of shipyard manufactured floating nuclear plants has a lot going for it in Finland, the most critical hurdles might come from the nuclear safety regulator, STUK. It is hard to estimate how STUK will regulate such a novel concept beforehand. Nobody, not even STUK, has prior experience, and the current regulations have been written for large on-land, water-cooled reactors that produce electricity. It is not clear, for example, what kind of role STUK would play if an FNPP would be constructed in Finland and exported to another country to produce energy there. Would it need licensing in Finland, and if yes, to what extent (and why)?

On the other hand, if we would buy an imported FNPP from someone else, say South-Korea, STUK would handle the design licensing and inspection on manufacturing as it does with other imported nuclear technology today. It seems clear that strong cooperation between national regulators would be beneficial to avoid doing the same (expensive) things multiple times.

The heavy licensing work for the vessel needs to be done just once, on the first one. It can then be copied for subsequent vessels, resulting in much lighter licensing work for them. Smaller changes and improvements to the design can also be reviewed individually without need for completely new re-licensing process. The site needs to be licensed as well, but in the same way, if multiple FNPP's of the same design are sited at the same location, one license suffices, and same goes for the operator and their capability. When it comes to the manufacturing process, the intensity of STUK involvement can be decreased over time when serial production proceeds and starts giving good results regarding quality and safety.

A lot is unclear, and a lot depends on the details. How is a "mobile" powerplant/site handled under current legislation and regulations? It would need a thorough inspection to make sure there are no "hard obstacles" that would prevent this kind of siting. Another question is where and how is fuel loading done, or system testing? If these are done at a Finnish location, the situation is quite different from it happening somewhere else. On a general note, the licensing of a floating NPP

47 https://www.talouselama.fi/uutiset/nesteella-on-porvoossa-ongelma-johon-se-etsii-nyt-kuumeisesti-ratkaisua-uskomme-vahvasti-vedyn-paalle-rakennettaviin-sahkopolttoaineisiin/2b269564-fbab-4e91-908a-92c25bfabbe0

itself should not be that different to licensing a normal, land-based power plant. It needs to be designed and manufactured as safe, and that safety needs to be proven to be high enough.

And what about refueling, and managing the fresh spent fuel? In my discussion with STUK experts, some potential ideas came up regarding spent fuel management. As such, freshly it is very "hot" and radioactive, so it would likely be a good idea to cool it down inside the FNPP for several years, as is done with land-based reactors as well. At some point, it might be a good idea to move the cooled-down spent fuel into a central facility for intermediate storage. This facility could handle spent fuel from multiple vessels and would be a "nuclear facility" by itself. This facility might or might not be at the same site as the facility for the eventual decommissioning of the vessel itself.

Whether different parts of the vessel need to be "nuclear grade" depends on the safety case. If something is an essential part of the nuclear safety case, it needs to be nuclear grade. As an extreme case, if the vessel is designed as "unsinkable", then most of the vessel might need to be nuclear grade, as "unsinkability" is an essential part of the safety case. But if the vessel is designed so it can be sunken, then much fewer parts needs to be nuclear grade.

As the vessels would be located on water, emergency cooling could be designed to work passively with seawater. Then again, the vessels would need to be able to handle extreme weather conditions, floods and so forth, and this ability needs to be proven.

In Finland, dual-use goods and technology exports are handled by Ministry of Exterior's Export Control Unit. If an application to export a working nuclear power plant from Finland arrives, it could be interesting times as nothing like this has ever been done and we lack broad international agreements on such matters at the moment. These are just a handful of the issues that would need resolving if we would start manufacturing or operating such plants, but so far, they do seem resolvable, if sufficient political will exists.

It is clear that a major effort like this needs to have very broad and clearly communicated political support. Political uncertainty increases the risk and cost of financing for everyone involved. Legally, nothing would prevent such projects from getting underway, although the legislation can and should be improved to lower the initial risk. Support is also needed from the supply chain, partners, shipyards and their communities and stakeholders.

The result would be a whole new industrial sector created in Finland, combining many of the current major industries. The implications for future high-quality jobs, export revenue, and positive environmental "handprint" are enormous. As such, one would hope there would be broad political support.

Even though Finland has a lot of potential both economically and in reducing CO_2 emissions, the larger potential lies in exports, as discussed in the next chapter. Starting to manufacture floating NPPs at Finnish shipyards would greatly help the shipyards in a difficult situation. The nuclear part would offer considerable growth for the nuclear industry and related services, as would the electrolysis and e-fuels refining part. We could also leverage our world-class expertise in nuclear waste management.

Opportunities to Make a Difference

"We know how to make nuclear as expensive as we want. Now we need to learn how to make it as low cost as possible while still safe."

To make cheap enough substitutes for the myriad of fossil fuel use cases we have today, we need to have low cost (and then very low cost) hydrogen production.

This requires several things:

- Very cheap energy input.
- The energy is delivered at high reliability, 8000+ h/a.
- Cheap electrolyzers.
- Highly efficient high-temperature electrolysis, requiring hot steam.

The proposed shipyard manufactured nuclear vessels can tick all those boxes if we make them low-cost enough through smart design and serial production. We will also need sensible and streamlined regulation that focuses on achieving acceptable levels of nuclear safety at acceptable cost instead of maximum nuclear safety at any cost. Indeed, the latter leads to much lower overall safety for both current society and future generations. We will keep using fossil fuels more and longer if there are no cost-competitive clean alternatives.

On the other hand, there are no ways to make otherwise low-cost wind or solar more reliable than they are today, not without adding significant costs through additional hardware such as energy storage. This might change with time and further development, but that is no argument for leaving other promising pathways unexplored. Further, the massive scales we will need for this hydrogen means that land use and materials inputs become more of a consideration.

Previously the study has referred to a 600 MWe floating NPP as a potential size to manufacture at several Finnish shipyards, with a combined output of multiple units per year. The following section presents three concepts for FNPPs taken from a recent report commissioned and published by Electric Power Research Institute (EPRI, 2021[48]). These are just examples of the possibilities, but as they have sufficient details on dimensions, costs, and equipment, they are more than suitable to be used as representative examples in this study.

48 https://www.epri.com/research/products/000000003002018348

Examples of FNPP Designs

The aim of shipyard manufactured FNPPs running on nuclear energy is twofold: 1) Bring down the cost of clean energy products and 2) enable a step-change in scalability and rate of deployment. The costs depend on many assumptions such as cost of capital, assumed size and lifetime of the facility, whether multiple products are produced at the facility, etc. A recent report commissioned by EPRI investigates the potential costs of some key products:

- Ammonia to be used as a carbon-neutral ship ping fuel or for fertilizers in agriculture.
- Carbon-neutral (or even carbon-negative) kerosine/jet A for aviation use.
- Electricity.
- Hydrogen.
- Desalinated water (through multi-stage distillation, which uses sub-100°C heat as the primary energy source, similar to what can be used for district heating).

The EPRI report has four deployment scenarios it inspects, three of which are focused on shipyard-manufactured offshore vessels with nuclear reactors as the power source. The fourth is an onshore Gigafactory-type facility. The conversion rate used for euros is \$1 = 0.9€. The prices are for an Nth-Of-A-Kind, serial manufactured product (NOAK), not a First-Of-A-Kind (FOAK). Below is a summary of each of the shipyard scenarios with discussion in the context of this study. The numbers used are not from Finnish shipyards, so the costs might differ.

Scenario 1 – Ammonia Production for Marine Shipping

Scenario 1 includes a large energy production vessel

(FPSO[49]) with:

- The vessel with the nuclear heat sources (2x 600MWe reactors).
- Hull and power island.
- High temperature electrolyser.
- Air separation unit for nitrogen capture.
- Ammonia synthesis (Haber-Bosch) unit.
- Storage for ammonia.
- Crew quarters for ~500 members.

The total cost of the vessel is $1.7 billion (1.53 B€). Table 3 below has the breakdown of costs between parts and modules for a NOAK facility.

Table 3: Capital costs breakdown for the large FPSO producing ammonia.

Ammonia Production FPSO Capital Cost	Million USD (2019)
High-temperature electrolyzer	$380
Nitrogen Generation (cryogenic air separation unit)	$48
Ammonia synthesis (Haber-Bosch) equipment	$290
Piping, instrumentation, electrical, and integration subsystems	$98
Subtotal, electrolyzer, N2 generation, ammonia synthesis, and other subsystems	**$870**
FPSO nuclear heat source block (2x600MWe)	$120
Balance of hull and power block	$740
Subtotal, hull and power block	**$860**
Total Overnight Capital Cost (OCC)	**$1,700**

Such a vessel can produce 3,300 tonnes of ammonia per day, corresponding to 12,000 barrels of oil equivalent (BOE). Production capacities and other key specifications are listed in table 4.

49 FPSO means Floating Production, Storage and Offloading vessel, such as those used in the offshore oil industry.

Table 4: Ammonia production Potential of a large FPSO

Ammonia Production Potential	
Thermal capacity (MWt)	2,600
Electric capacity (MWe)	1,200
Annual H_2 production capacity (tonnes)	220,000
Annual NH_3 production capacity (tonnes)	1,200,000
Daily NH_3 production capacity (tonnes/day)	3,300
Daily NH_3 production capacity (BOE/day)	12,000
Physical Specifications	
Platform dimensions (m)	L: 393; W: 64; H: 105; Draft: 13
Lifetime (years)	30
Displacement (tonnes)	152,000

If such a vessel, with a capital cost of $1.7 billion, would have a crew of 500, a 30 year assumed payback time with a 7% interest rate, it would have total annual expenses of $340 million (~300 M€). **The levelized cost of ammonia would therefore be $230 per tonne or $62 per barrel of oil equivalent, BOE (in euros, €207 / t and €56 / BOE)**. This is competitive with long-term average prices of both ammonia and other fuels we could replace with ammonia, such as shipping fuel. It is extremely competitive with recent ammonia prices, as the cost per ton broke $1,000 in October 2021[50] and $1,400 per short ton in January 2022[51], thanks mainly to surging natural gas prices.

The breakdown of the levelized cost assumptions is in table 5 below.

50 https://farmdocdaily.illinois.edu/2021/10/management-decisions-relative-to-high-nitrogen-fertilizer-prices.html
51 https://www.dtnpf.com/agriculture/web/ag/crops/article/2022/02/11/january-slow-month-fertilizer-sales

Table 5: Levelized cost of ammonia with a large FPSO.

Levelized Cost of Ammonia		USD 2019
Annual ammonia production (tonne)	1,200,000	
Capital cost, entire FPSO		**$1,700,000,000**
Capital period (years)	30	
Interest rate	7%	
Annualized capital expense		**$140,000,000**
Direct crewmember count on staff	500	
Annual expense per crewmember	$100,000	
Annual staffing expense		$50,000,000
Annual fuel and consumables expense		$94,000,000
Annual maintenance (2.5% of OCC)		$43,000,000
Annual administration, insurance, fuel operations, and decommissioning expense		$9,500,000
Total annual expense (USD)		**$340,000,000**
Levelized cost of ammonia (USD/tonne)		**$230**
Levelized cost of ammonia (USD/GJ)		**$10**
Levelized cost of ammonia (USD/BOE)		**$62**

In Finland, Wärtsilä is already studying ammonia as a fuel in marine shipping and has also been developing suitable engines[52].

This type of ammonia production would also be insensitive to the fluctuations of fossil fuels prices, let alone shortages or disruptions in the markets such as those seen in recent months due to Russia attacking Ukraine. This would increase food security and decrease CO_2 emissions in the agricultural sector. The importance of having a reliable and stable-priced source of critical agricultural inputs can hardly be overstated[53].

52 https://www.wartsila.com/media/news/14-07-2021-wartsila-launches-major-test-programme-towards-carbon-free-solutions-with-hydrogen-and-ammonia-2953362

53 See for example https://www.statista.com/statistics/1278057/export-value-fertilizers-worldwide-by-country/

Scenario 2 – Jet-A for Aviation

Scenario 2 has the same basic FPSO configuration as scenario 1 with 2 x 600MWe reactors on a 393 meters long and 64 meters wide vessel. The end-product is entirely different, as it is a hydrocarbon (jet fuel such as the industry-standard Jet-A) instead of a nitrogen/hydrogen-based fuel (ammonia). This also means that there needs to be a source of sustainable carbon to make the fuel, which introduces complications. Nitrogen is relatively easy to separate from the air, which is 78% nitrogen, but there is only 0.04 % of carbon dioxide in the air.

The FPSO in scenario 2 includes:

- The vessel with the nuclear heat sources (2x 600MWe reactors).
- Hull and power island.
- Hight temperature electrolyzer.
- Calciner.
- Fischer-Tropsch facility.
- Crew quarters for ~500 members.

There are several options to source the carbon from, each with its ups and downs. This scenario uses crushed limestone as the source of CO_2, which can even be a carbon-negative source, as explained below. Other sources include:

- Sustainable biomass/bioenergy combustion capture.
- Direct air capture (DAC) or separation from seawater.
- Cement manufacturing.

One can also capture CO_2 from fossil fuel power plants, but that will only recycle the fossil CO_2 once, so it is not sustainable in the long run. The total overnight capital cost of the FPSO is $1.4 billion, with a breakdown in table 6.

Table 6: Capital cost breakdown of a jet fuel production FPSO.

Jet Fuel Production Ship Capital Cost	Million USD (2019)
Cost of calciner	$2.1
Cost of electrolyzer, including all piping and subsystems	$210
Cost of F-T reactor components	$220
Subtotal, main components	**$510**
Instrumentation and Control	$5.7
Electrical Systems	$18
Building-integration structures adjusted for ship-based scenario	$10
Subtotal, other subsystems	**$33**
FPSO nuclear heat source block	$120
Balance of hull and power block	$740
Subtotal, hull and power block cost	$860
Total Overnight Capital Cost (OCC), million USD	**$1,400**

The FPSO would produce 9,600 barrels of oil equivalent (BOE) of jet fuel per day or 4 million barrels (bbl) per year. Today, the world uses over 2,000 million barrels of jet fuel per year, and jet fuel use is projected to more than double by 2050. This means there is demand for 500+ such vessels, producing carbon-neutral (or carbon-negative) Jet-A. The production breakdown is in table 7.

Table 7: Jet fuel production potential of a large FPSO.

Jet A Production Potential	
Thermal capacity (MWt)	2,600
Electric capacity (MWe)	1,200
Electrolyzer H_2 and CO daily production (kg/day)	5,000,000
Annual jet fuel production (tonne/year)*	510,000
Annual jet fuel production (bbl/year)*	4,000,000
Annual jet fuel production (BOE/day)*	9,600
Physical Specifications	
Platform dimensions	L: 393m; W: 64m; H: 105m; Draft 13 m
Lifetime (years)	30
Displacement (tonnes)	152,000

The levelized cost of jet fuel depends on the assumptions for where the CO_2 is acquired and at what cost. As mentioned above, this scenario assumes limestone as the source at $7 per tonne. The detailed assumptions for the levelized cost of Jet fuel, at $82 per barrel (74 €/barrel), are presented in table 8.

Finnair & Neste

Finnair is Finland's national airline and arguably an important strategic asset for Finland. The gross emissions of Finnair aviation activities in 2019 were 3.5 million tons of CO_2, and the company aims to reduce these emissions to reach carbon neutrality by 2045[1].

Finnair is planning to increase procurement of biofuels (or SAF, sustainable aviation fuel) throughout 2025 so that by then, the company will use €10 million per year for SAF. According to Neste, the SAF supplier for Finnair at the Helsinki-Vantaa airport, SAF is 3-4 times more expensive than fossil-based aviation fuel and reduces emissions by as much as 80% compared to fossil jet fuel. The target cost for the FPSO in scenario 2 for carbon-neutral jet fuel, $82/barrel, is below the long-term average price of jet fuel, which is $94/barrel.

Today, Neste produces 100,000 tonnes of SAF in its Porvoo refinery. Finland uses 800,000 tonnes of jet fuel annually, of which Finnair uses around half a million tonnes. A single large FPSO, as seen in scenario 2, produces 510,000 tonnes of carbon-neutral jet fuel per year, not at 3 to 4 times the cost of regular jet fuel, but at a comparable cost.

1 The numbers in this case study are from this article (in Finnish): http://www.lentoposti.fi/uutiset/finnair_ja_neste_pienent_v_t_yhteisty_ss_lentoliikenteen_p_st_j_kohti_hiilineutraaliutta

Table 8: Breakdown of cost structure for levelized cost of jet fuel production

Levelized Jet Fuel Cost		Million USD (2019)
Annual jet fuel production (tonne/year)*	510,000	
Annual jet fuel production (bbl/year)*	4,000,000	
Total FPSO capital cost		$1,400,000,000
Capital period (years)	30	
Interest rate	7%	
Annualized capital expense		$110,000,000
Direct crewmember count on staff	500	
Annual expense per crewmember	$100,000	
Annual staffing expense		$50,000,000
$CaCO_3$ (limestone) consumption, tonne/year	3,700,000	
Cost of limestone USD/tonne	$7	
Annual limestone expense		$25,000,000
Annualized reactor consumables expense		$94,000,000
Annual fuel and consumables expense		**$120,000,000**
Annual maintenance expense (2.5% of OCC)		**$35,000,000**
Annual administration, insurance, operations, and decommissioning expense		**$9,500,000**
Total annual expense		**$330,000,000**
Levelized cost of jet fuel ($/tonne)	**$640**	
Levelized cost of jet fuel ($/bbl)	**$82**	

Scenario 3 – Co-generating Ammonia, Electricity, and Desalinated Water

The third scenario has a smaller vessel with just half the power capacity as the larger vessels in scenarios 1 and 2. Instead, it offers some exciting opportunities for effective co-generation of different energy products, from electricity to ammonia to desalinated water (made with waste heat that can be directly used for district heating instead). It is ideally situated near shore, where the products can be transported via cables and pipelines to the markets onshore.

The FPSO in scenario 3 includes:

- The vessel with the nuclear heat sources (1x 600MWe reactor).
- Hull and power island.
- Hight temperature electrolyzer.
- Desalination equipment (multiple effect desalination, MED).

- Air separation unit for nitrogen capture.
- Ammonia synthesis (Haber-Bosch) unit.
- Storage for ammonia.
- Crew quarters for ~200 members.

The total OCC for the multi-product FPSO is $1.5 billion (1.35 B€). The breakdown of the various parts of the vessel and their costs are presented in table 9. Importantly, desalination equipment represents a third of the overall cost of the system, at $540 million. If this FPSO were modified to produce district heat instead, the total cost would be dramatically lower.

Table 9: Capital costs for the smaller, multi-product FPSO

Multi-Product Production Ship Cost		2019 USD
Desalination Equipment (MED)		$540,000,000
Electrolyzer		$140,000,000
N_2 generation (cryogenic air separation unit)		$17,000,000
Ammonia Synthesis (Haber-Bosch)		$110,000,000
Piping and transmission		$50,000,000
	Subtotal, component cost	**$860,000,000**
Instrumentation and Control		$3,200,000
Electrical Systems		$10,000,000
Building-integration structures adjusted for ship-based scenario		$5,700,000
	Subtotal, other subsystems cost	**$19,000,000**
FPSO nuclear heat source block		$80,000,000
Balance of hull and power block		$500,000,000
	Hull and power block cost	**$580,000,000**
	Total Overnight Capital Cost	**$1,500,000,000**

This smaller multi-product FPSO would have half of the energy production capacity compared to the ships in scenarios 1 and 2. Co-generation of multiple products, especially when one product (district heat or desalinated water) is made with lower quality heat that would otherwise go primarily to waste, can significantly increase the overall efficiency of the FPSO. Having multiple products can also increase flexibility and the ability to follow market demand by producing products that have the most demand, at least to a point. On the other hand, all equipment has capital, operational, and maintenance costs, so they should be used as much as possible.

Table 10: Breakdown of the production profile for the smaller multi-purpose production FPSO

Primary Energy Source	
Thermal capacity (MWt)	1,300
Electricity generation capacity (MWe)	580
Capacity factor of production (applies to all product lines)	90%
Polygeneration Production Potential	
Electricity	
Thermal resource-fraction sold as electricity (%)	20%
Electricity production, maximum electric power (MWe)	120
Electricity available to sell (MWhe/year)*	920,000
Water	
Thermal resource-fraction (above recovered waste heat) sold as water (%)	1%
Water production rate (m^3/day)	330,000
Water available to sell (m^3/year)*	110,000,000
Ammonia	
Thermal resource-fraction sold as ammonia (%)	79%
Ammonia production, peak production capacity (tonne/hour)	44
Ammonia available to sell (tonne/year)*	230,000
Physical Specifications	
Platform dimensions	L: 284.5m, W: 56m, H: 31.5m
Lifetime (years)	30
Displacement (tonnes)	76,000

Table 11 breaks down the levelized costs for different products with the given assumptions. Using the waste heat for district heating would likely improve the economics further, as CAPEX would be significantly lower without the desalination unit at that scale.

Table 11: Levelized cost for the different products of the smaller multi-purpose FPSO

Levelized Product Cost		2019 USD
Electricity (MWhe/year)	920,000	
Water (m^3/year)	110,000,000	
Ammonia (tonne/year)	230,000	
Overnight capital cost (entire FPSO)		$1,500,000,000
Capital period (years)	30	
Interest rate	7%	
Annualized capital expense		$120,000,000
Direct crewmember count on staff	200	
Annual expense per crewmember	$100,000	
Annual staffing expense		$20,000,000
Annual fuel and consumables expense		$62,000,000
Annual maintenance expense (2.5% of OCC)		$36,000,000
Annual administration, insurance, operations, decommissioning expense		$9,500,000
Total annual expense		**$250,000,000**
Levelized electricity cost (USD/MWhe)	**$43**	
Levelized water cost (USD/m^3)	**$1.30**	
Levelized ammonia cost (USD/tonne)	**$290**	

To summarize, below is a rough estimate of the costs for different products that could be achieved with NOAK FNPPs designed and manufactured for the purpose in Finland. Advanced reactor technologies, mass manufacturing, and improved productivity investments at shipyards can bring costs down even further.

- Electricity: <40 €/MWh for baseload, depending on the configuration.
- Industrial process steam: ~15 €/MWh (derived from the cost of electricity).
- District heat with CHP: ~10 €/MWh (derived from the cost of electricity).
- Desalinated water: <1.5 €/m^3.
- Hydrogen: ~2€/kg.
- Ammonia: <300 €/tonne.
- Jet-A: <90€/barrel.

These costs seem extremely promising, as they are pretty competitive with fossil-based alternatives, even without significant carbon fees or subsidies. The sizes of potential markets for different products are discussed below.

Just Combined Heat and Power?

What if an FNPP would produce just electricity and perhaps heat for a district heating network? The CAPEX cost for a 600 MWe vessel manufactured at a Finnish shipyard[54] would be roughly 2,500€/kWe, according to the lead author of the EPRI study featured above. This would translate to a CAPEX share of 21€/MWh. This can decrease by lowering the financing cost, such as with government loan guarantees, direct government funding, or using the Mankala-model for ownership. Assuming an optimized design with reduced staffing would mean 10€/MWh of OPEX, and a further 8€/MWh for fuel and other OPEX costs brings the total LCOE to 39€/MWh. Selling district heat through co-generation of power and heat would lower the LCOE, and mass production of multiple units might bring CAPEX lower, closer to 2,000 €/kW.

Business Opportunities

"A goal without a plan is just a dream."

This study has made several assumptions and comes to several conclusions regarding the cost-reduction potential of shipyard manufactured offshore energy vessels. One can and should challenge these assumptions and perhaps make calculations using their numbers and estimates to evaluate the potential.

54 Assuming somewhat higher costs compared to South Korean shipyards.

But one thing remains clear: if the numbers presented here are even somewhat close to possible, the opportunity is enormous, both economically and environmentally. This means that someone will start doing this at some point, likely soon. As we learned earlier, numerous actors are increasingly looking into this already. So the question we should answer is whether Finland wants to be involved in this sector among the first movers or not. Given the many critical pieces of the puzzle Finland already has, one would think it a missed opportunity not to get involved early on.

There are several business sectors and opportunities that early involvement would open for Finland, each with a different size and profile. They often support and build on each other.

1. Designing or manufacturing the vessels, including the supply chain

Finnish shipyard industry could design and manufacture these vessels (with or without the actual nuclear reactor installation) and sell them on the global market, as they can be towed practically anywhere. Given that a practical climate project would likely require hundreds of these vessels to be deployed each year, the market is enormous. Many components and materials (such as steel) can also be supplied domestically, and the serial production of such vessels might create new business sectors for Finnish suppliers.

2. Owning/operating the vessels for domestic and nearby markets

It would make sense to start operations and sell the products domestically or in nearby countries open to nuclear energy, starting around the Baltic Sea and expanding from there. The products include electricity, district heat, process heat, hydrogen, and other e-fuels. Near-shore siting would enable the cost-effective transfer of district heat and electricity to coastal cities and industrial parks without reserving and permitting land for energy production facilities. The business model could be based on mutual ownership (even Mankala-model), long term PPA-contracts, or some other model.

3. Owning/operating the vessels and selling the products for the broader market

There is practically infinite demand for competitive clean energy products such as e-fuels globally. Finnish actors could manufacture, own and operate such vessels near Finnish coasts and ship the products, be it hydrogen, ammonia, or hydrocarbons, into nearby markets like those in mainland Europe. To cater to needs further away, shipping costs play an increasing role. In these cases, it might be worth considering moving the facility closer to the markets, perhaps seeking local companies for partnerships and co-ownership.

4. Operating the vessels for other owners

In addition to (or instead of) manufacturing the floating nuclear barges, Finnish nuclear companies can sell operations as a service to others. Combined with manufacturing the FNPPs, this creates a possibility to sell a "clean energy as a service" -solution. Combining this with the following two points, decommissioning and spent fuel management, would make this an even more salient and valuable service.

5. Decommissioning services

Eventually, these vessels need to be retired and depending on the vessel, the lifecycle is likely between 25 to 60 years. Mobile power stations can be towed into a central location for decommissioning, materials recycling, and waste product management, perhaps including spent nuclear fuel or the reactor systems themselves.

6. Spent fuel management

Combined with operational services, we could include spent fuel management and the final repository as a service. This is a unique and valuable proposition since Finland is the forerunner in building and (soon) operating a final repository for spent nuclear fuel. This would represent a genuine "turnkey" service, including turning the key to start operations, operation services, and eventually taking responsible care of the produced waste. This would be especially valuable for customers and countries that do not have the necessary institutions and infrastructure (or political will) in place to manage radioactive waste. Further, given that the European Taxonomy for sustainable investments complementary delegated act has a nuclear waste repository plan (or access to one) as one of the conditions for Taxonomy inclusion, this certainly could add to Finnish competitiveness.

7. Consulting

With experience in designing, manufacturing, operating, and eventually decommissioning such vessels and spent fuel management, Finnish companies could sell this expertise as consulting services to other newcomers and actors in the field. But this lucrative expertise is unlikely to manifest without the work and effort first put into "walking the walk."

Market Overview for Clean Energy and Fuels

One of the main strengths of the NFPPs is the versatility and flexibility when it comes to their end-product, as all kinds of synthetic fuels manufacturing can benefit from shipyard manufacturing, reliable energy availability, and flexible offshore siting of facilities.

The FNPPs can produce electricity transferred to land for various uses or include electrolyzers and other equipment to make other e-fuels, which can then be shipped or sent through pipelines to end-users. A thorough market analysis is not within the scope of this study. Still, this chapter offers broader discussion and insights on the unfolding market for various clean energy products in Finland, Europe, and even globally. It also includes some smaller, more concrete case studies.

Powering Europe

Europe has been heading into an increasingly precarious situation. A lot of firm and dispatchable capacity (nuclear, coal) is being shut down while more weather-dependent wind and solar are added. And while energy produced over a year might not change much when replacing a thermal power plant with wind and solar, the ever-important delivery of power during that year's seconds, minutes, and hours will be significantly affected.

This process started years ago. By early 2022, Germany has shut down all but 3 of its 17 nuclear reactors during the last ten years, going from 20.5 GWe to 4 GWe. Without quick and decisive actions from key politicians, the last three plants will also be closed at the end of 2022. Belgium was following suit with its 7-reactor (6 GWe) nuclear exit by 2025, even as nuclear produced half of Belgian electricity in 2021. The gas plants that Belgium was planning to replace the nuclear production have also run into problems getting their permits.[55] Overall, the Belgian transmission system operator Elia has stated that 3.6 GW of new thermal capacity will be needed by 2025. Belgium is already importing a fifth of its electricity.

The closures will start with one reactor in 2022 and the second in 2023. In March 2022, Belgian politicians decided to prolong the operations of the two most recent nuclear plants by ten years into 2035, considering the Russian invasion of Ukraine and the unfolding energy crisis. Still, five reactors are facing premature closures.

Switzerland has also, in principle, decided to phase out nuclear power over time with a referendum taken in 2017 banning the construction of new nuclear but allowing the existing plants to operate as long as deemed safe. Nuclear, at 3 GWe from 4 reactors, has supplied roughly one-third of Swiss electricity as well as district heating from two plants. The first plant closed was Mühleberg in 2017, a 373 MW single-reactor power plant. It remains to be seen when the other reactors are shut down and what they will be replaced with, as renewables deployment has been slow. Today, Switzerland is acting as an import/export hub for countries like France, Austria, and Italy, both importing and exporting.

Sweden has already shut down some of its nuclear plants, and it remains to be seen what happens next, but the country has seemingly started to awaken to its capacity and transmission problems. Recently, a new actor, Kärnful Next, announced they would be pushing for small reactors in Sweden[56], which will require a change in legislation.

France also has a mixed situation. On the one hand, the country pledged to reduce the nuclear share of electricity production by a third, from 75% to 50% by 2025. This has since been delayed to 2035. The phase-down started with the closure of Fessenheim-2 in 2020.[57] On the other hand, there are conditions of security of supply and emissions now attached to the shut-down plan, and the energy crisis of 2021 and the Russian invasion of Ukraine in 2022 might have taught a lesson or two on the wisdom of prematurely shutting reliable electricity production.

55 https://www.reuters.com/markets/commodities/belgian-government-reaches-deal-nuclear-exit-media-2021-12-23/

56 https://www.vainsights.se/articles/803759/2022-03-14-12-25-34-karnfull-och-ge-hitachi-i-smr-samarbete-

57 https://world-nuclear-news.org/Articles/France-completes-closure-of-Fessenheim-plant

Further, the nuclear capacity of France has been capped at 63.2 GWe, meaning that in the future, some reactors might operate at lower capacity factors or produce something else than power for the grid, like hydrogen. Be that as it may, the French fleet will also age, and some shut-downs are inevitable. President Macron has discussed building up to 14 new EPR reactors in France by 2050[58]. What the net result will be at the end of the day is anyone's guess at this point, as laws and targets can be, and have been, rewritten multiple times along the way.

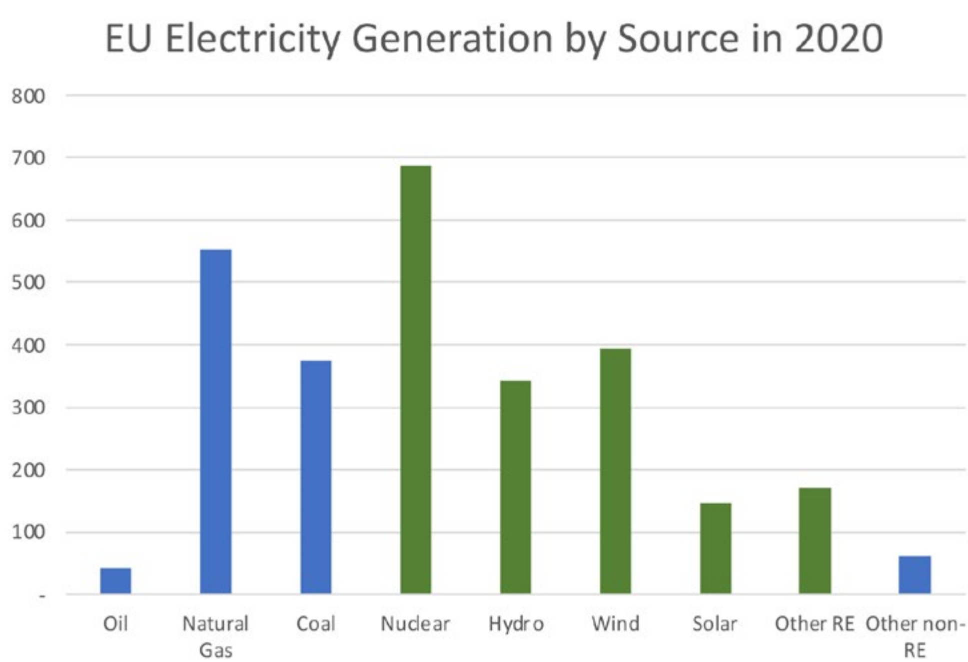


Figure 14: A lot of European electricity still comes from firm and reliable sources such as nuclear, hydro, natural gas, and coal.

In addition to nuclear, there are the planned coal exits and the coal exits that will happen due to escalating emissions prices in the EU ETS. These will remove another firm power source and spinning reserve from the European grids. Germany alone has over 40 GWe of coal capacity, and there are plans to shut it down in the 2030s – although these plans are now under revision due to Russian gas suddenly being seen as an unbearable risk for supply security. In 2020 EU had 166 coal plants in 18 countries with a total capacity of 112 GW[59]. From a climate target perspective, all European coal capacity should be shut down by mid-century, and there isn't much room for fossil gas either.

The UK is somewhat of an exception, in a positive way. Their government recently announced the creation of a new government agency called "Great British Nuclear" to bring forward new projects, backed up by substantial funding[60]. UK PM Boris Johnson also stated that UK will build up to seven new reactors to increase the country's energy self-reliance. The UK has a lot to do, but it is among the few countries in Europe that have started to take a pragmatic, technology neutral approach in dealing with their climate and energy situation. The Brits are likely to be more open for cooperation in the nuclear field and deploying and using novel concepts such as FNPPs in the coming years.

In short, there is a grand experiment about to take place in mainland Europe on how electricity grids can be operated and kept stable without the critical factors in that stability – dispatchable production with large spinning reserves – and it is only getting started. Cutting a significant chunk of natural gas from the supply side will

58 https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/france.aspx

59 https://ec.europa.eu/jrc/sites/default/files/factsheet_on_eu_trends_coal_peat_oil.pdf

60 https://www.gov.uk/government/news/major-acceleration-of-home-grown-power-in-britains-plan-for-greater-energy-independence

make an already precarious and challenging task much harder. On the other hand, frequent rolling blackouts will be prevented at almost any cost. We perhaps got a taste of that cost during the energy and gas crisis that started in 2021.

Replacing retiring capacity is only one side of the story. As Europe decarbonizes its industry and transportation, electricity demand is set to soar. Some use cases of fuels will be directly electrified, such as shifting from petrol and diesel cars to EVs. Some will be indirectly electrified, such as coke used in iron reduction replaced by hydrogen or marine fuels replaced by ammonia. Depending on the depth of decarbonization and how different technologies scale up, we are easily looking at doubling or tripling electricity consumption. A significant share of this increased demand will be for reliable, dispatchable power, with a bonus for flexible load-following capabilities.

All this means that there should be a rapidly growing demand for reliable and firm power from the 2020s and 2030s onward. But when this demand becomes acute, it is too late to start planning, as:

- Planning, licensing, and building a giant nuclear plant can take 10 to 15 years, even with experienced crews and supply chains.

- Adding even more variable renewable energy sources is not a solution to a problem primarily caused by them: the availability of *power* when it is needed.

- Adding fossil-fueled generation capacity is a faster option, especially with gas turbines, but most agree that this is hardly a sustainable solution from a climate point of view. It is becoming increasingly unsustainable also from the security of supply point of view.

- Adding short-term energy storage like batteries will help grid stability, but they are relatively expensive and not scalable to industrial scale and multi-day storage needs.

Therefore, there might well exist a significant market for shipyard-built nuclear ships that can be constructed faster, do not require a multi-year siting process, and can be towed to a location near the demand. The eventual size of this market depends on many things down the road. **Right now, it seems it might well be in the multiple dozens of gigawatts in the 2030s, just for flexible power production in Europe.**

Hydrogen

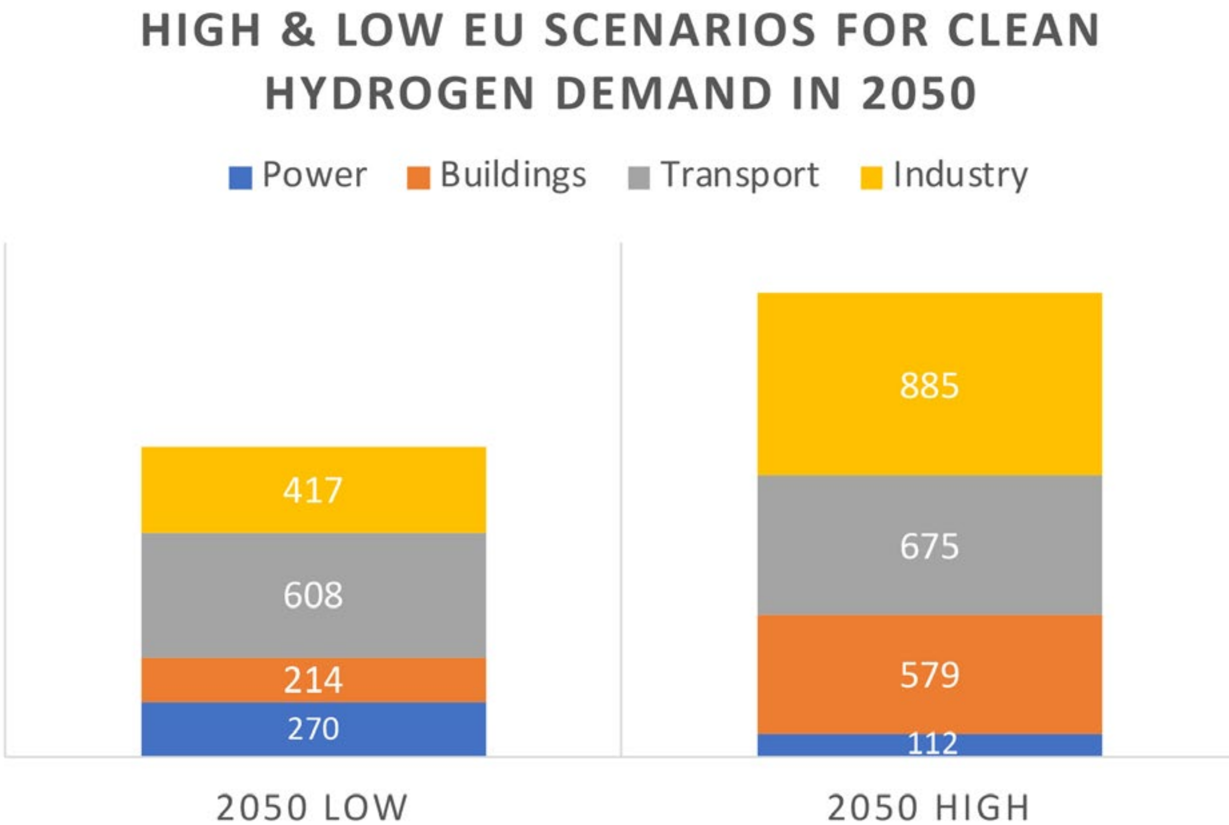
Today, some 4,500 TWh (120 Mt) of hydrogen is produced and used worldwide, of which 70 Mt is dedicated production[61], 99% made from fossil fuels. Hydrogen production causes 830 Mt of CO_2 emissions per year (15 times the emissions of Finland). Most of this hydrogen is used to produce ammonia or in oil refineries.

Producing the "dedicated share" of hydrogen with water electrolysis would use almost 4,000 TWh of clean electricity, close to the current total EU electricity use. This would take roughly 500 GWe of nuclear power to produce, more than the current global nuclear fleet, and more than 1,000 GW of wind power – again, more than we currently have globally (in 2020, we produced roughly 1,600 TWh of wind globally)[62].

By 2050, we should not only decarbonize our current hydrogen production but also expand the production and use of clean hydrogen perhaps tenfold, replacing fossil hydrocarbons in many sectors with synthetic fuels. The future market for clean hydrogen seems very big, but it needs to be very low-cost to be realized.

A recent study commissioned by Gasgrid[63] summarizes the macro-studies of the future clean hydrogen demand in Europe as follows. By 2030, the demand will be around 300 – 650 TWh, and by 2050, it will be between 1,500 and 2,250 TWh of hydrogen. Assuming an av-

61 The rest comes as byproduct from other activities.
62 BP Statistical Review of World Energy 2021.
63 https://gasgrid.fi/en/2021/12/16/finland-has-opportunities-to-become-the-leading-country-in-hydrogen-production/



erage efficiency of 75% for electrolysis, these numbers translate to 400 – 870 TWh of clean electricity demand by 2030 and 2,000 to 3,000 TWh by 2050.

Figure 15: The highest and lowest scenarios for hydrogen demand by sector in the EU by 2050. Data source: Gasgrid 2021

From a capacity perspective, we would need between 45 and 100 GWe by 2030 and 230 to 340 GWe by 2050, assuming power plants and electrolyzers running 24/7 at full power. One can multiply those capacity requirements 2 to 8 times with wind and solar.

Europe has a target of 6 GW electrolyzer capacity by 2024, increasing rapidly to 40 GW by 2030. Further, the EU Commission plans to have another 40 GW of electrolyzers in neighboring countries, supplying the EU with "renewable hydrogen[64]." Putting concerns of energy imperialism and security of supply aside, this is an ambitious goal compared to the current situation where the electrolyzers capacity is in the hundreds of megawatts in the EU. The targeted 6 GW would be able to produce around 1 Mt of hydrogen if working 8760 hours per year at full capacity (100% capacity factor, CF).

But energy sources do not operate at 100% CF, so the calculation above assumes 100% available grid power. Table 12 shows how much hydrogen different energy sources would produce at a specific capacity (GW) of electrolyzers. Solar has a 15% capacity factor, wind has

64 https://www.reuters.com/business/energy/europe-partners-set-beat-2030-green-hydrogen-capacity-target-says-eus-timmermans-2021-11-29/

40%, and nuclear has 90%. The percentages are indicative only, as any given plant might have a different capacity factor from the one shown in the table.

Table 12: The hydrogen produced in TWh from a given electrolyzer capacity with various energy sources.

	H_2 produced with different capacity factors, TWh/year			
Electrolyzer capacity, GW	Grid 100 %	Solar 15 %	Wind 40 %	Nuclear 90 %
1	9	1	4	8
6	53	8	21	47
40	350	53	140	315

One can look at it from two perspectives. First, one gets a smaller amount of hydrogen from a given capacity of electrolyzers when using weather-dependent energy sources like wind and solar. Or one needs more electrolyzers and wind & solar capacity to produce the same amount of hydrogen. Combining wind with solar increases the combined capacity factor, as sometimes the sun shines while the wind is not blowing and vice versa. Then again, this requires investing "twice" into energy production, and sometimes wind and solar produce energy simultaneously, leading to higher overproduction.

Even if the electrolyzers would use grid electricity in "real life," it is helpful to think of hydrogen production as a separate activity from the power grid for several reasons. First, the hydrogen demand can grow to be as large in capacity as our current electricity use or even larger, and it makes little sense to think of it as a "small subsection" of the power grid if it ends up the same size. Second, thinking of it as a separate system handily prevents one from double-counting the benefits or brushing the bottlenecks and problems under the rug in one's analysis.

As an example, people say that electrolyzers are needed to produce very low-cost hydrogen at a massive scale to displace fossil fuels in many sectors. People also say that electrolyzers would be great for using surplus production of variable wind and solar and help keep the grid stable. Both can't be done at the same time with the same electrolyzers. The second case does not lead to low-cost hydrogen produced at a large scale but mainly aims to manage the variability and overproduction problem high shares of wind and solar can lead to. Yet sometimes one gets the picture that people think we can "have the electrolyzer cake and eat it too." Thinking of hydrogen production as a separate dedicated facility prevents one from making this mistake.

Assuming the EU target of 40 GW of electrolyzers will be running at 90%+ capacity factors on average, they would produce over 300 TWh of hydrogen (~9 million tons) and draw some 450 TWh of electricity per year[65]. But assuming they will be operating on renewable energy alone (which seems to be the claim many likes to make), they might produce half of that or less. This is something we need a lot more clarity on from policymakers: are they assuming these electrolyzers to produce hydrogen 8000+ hours per year? And if so, why are they referring to "renewable hydrogen capacity," which is misleading if grid electricity is used?

Or on the other hand, if they do plan just to use dedicated renewable energy for the electrolyzers, it would be helpful to discuss the fact that there will be much less clean hydrogen available than one might assume. Further, this hydrogen will be relatively expensive given the low CF the electrolyzers will run at and result in smaller emissions reductions.

The economics matter as well. Suppose we go from 90%+ CF to around 45% CF for the energy source. In

65 If current commercial electrolyzer technology is used at ~70% efficiency.

that case, the price of hydrogen increases by roughly 80% if other assumptions are held constant.

Case Belgium – Power and Hydrogen

Today, Belgium produces roughly 404 ktons of hydrogen, corresponding to around 13.5 TWh of energy content. Most of this (~85%) is supplied with steam methane reforming of natural gas, causing significant emissions. The rest is produced as a by-product of various chemical processes. If this hydrogen were made with electrolysis (75% efficiency), it would increase annual electricity demand by 18 TWh. In 2020, Belgium used roughly 81 TWh of electricity, of which nearly half was produced with nuclear power. The government of Belgium previously decided to shut down the nation's nuclear sector by 2025, removing ~40TWh of clean electricity production, but by March 2022, the tone was already quite different[66]. In March, a decision was made to save two of the remaining reactors until 2035.

As more industry adopts hydrogen as a feedstock or an energy carrier for their processes, this demand will at least double by the 2040s. Overall, according to VLAIO 2020 study[67], electricity demand in Belgium will increase between 50% and 300 % (+40 TWh to +240 TWh per year). **Combined with the closure of the current nuclear fleet by 2035, Belgium needs 80 to 280 TWh of new clean electricity production by 2050**.

The study estimates the cost of hydrogen production from natural gas as below 2€/kg, rising to 2-5€/kg with carbon capture and storage and to 4-10€/kg with electrolysis driven by renewable energy sources. Most industries can't soak this kind of cost increase in a significant feedstock/energy source and remain competitive. As seen in this study, the nuclear option can offer a competitive solution even with natural gas, especially with both rising natural gas prices and rising prices for CO_2 emissions in the ETS.

66 https://t.co/j4DITDycou

67 https://www.vlaanderen.be/publicaties/naar-een-koolstofcirculaire-en-co2-arme-vlaamse-industrie

The Demand Numbers

Let's recap the numbers to get a feel for the demand and how it grows. Overall, electricity demand will increase by 40 to 240 TWh by 2050, depending on the scenario. In addition, up to 40 TWh of nuclear production will be lost due to a decision by the Belgian government. In the big picture, **Belgium will need to add 3-10 TWh of clean electricity production capacity per year, on average, for the next 28 years.**

If we look at just the demand for hydrogen, the situation is still sobering. The current demand for hydrogen is ~13.5 TWh (404 kton), supplied chiefly by fossil fuels, and this demand will grow to 30 TWh by 2045. All of this should be produced with clean energy. **Starting from 2025 and running to 2045, 1.5 TWh of clean hydrogen production needs to be added each year** (equals 2 TWh of electricity production, with 75% efficiency for electrolysis).

The Ships

A 500 MWe FNPP produces 4 TWh of electricity or 3 TWh of hydrogen per year. To meet the hydrogen demand in Belgium, one such vessel needs to be commissioned every other year, starting the project as soon as possible and running for 20 years. The ships can produce electricity and transmit that to the mainland for the electrolyzers, or include the electrolyzers onboard and send the hydrogen onshore via a pipeline.

The maximum total addressable market in Belgium – adding 280 TWh of clean electricity production capacity by 2050 – means 10 TWh of new production would need to come online each year, starting in 2023. This would mean one 1.2 GWe nuclear power plant built each year, or 200 giant wind turbines, each with a capacity of 12 MW, added each year for a total of ~6,000 turbines and 72 GW of capacity. Only the nuclear option would offer reliable power by itself. Further, the wind farms would take up a significant area. Using Dogger Bank, the world's largest wind farm (3.6 GW in total and 1,674 km^2 in area) under construction in the North Sea as a benchmark, 72 GW of offshore wind capacity would take up roughly 33,000 km^2, more than the land area of Belgium.

Figure 16: 6,000 wind turbines at 12 MW each and 72 GW total, sited on a 33,000km² offshore wind farm, would take up more space than the total area of Belgium. In reality, the wind parks would need space between them, so the actual size would be larger than the one marked on the map.

If this demand were met mainly with nuclear vessels, **1,000 to 1,500 MWe worth of FNPP capacity would need to be built each year, just for Belgium**. The program should start as soon as possible and run at least until 2050.

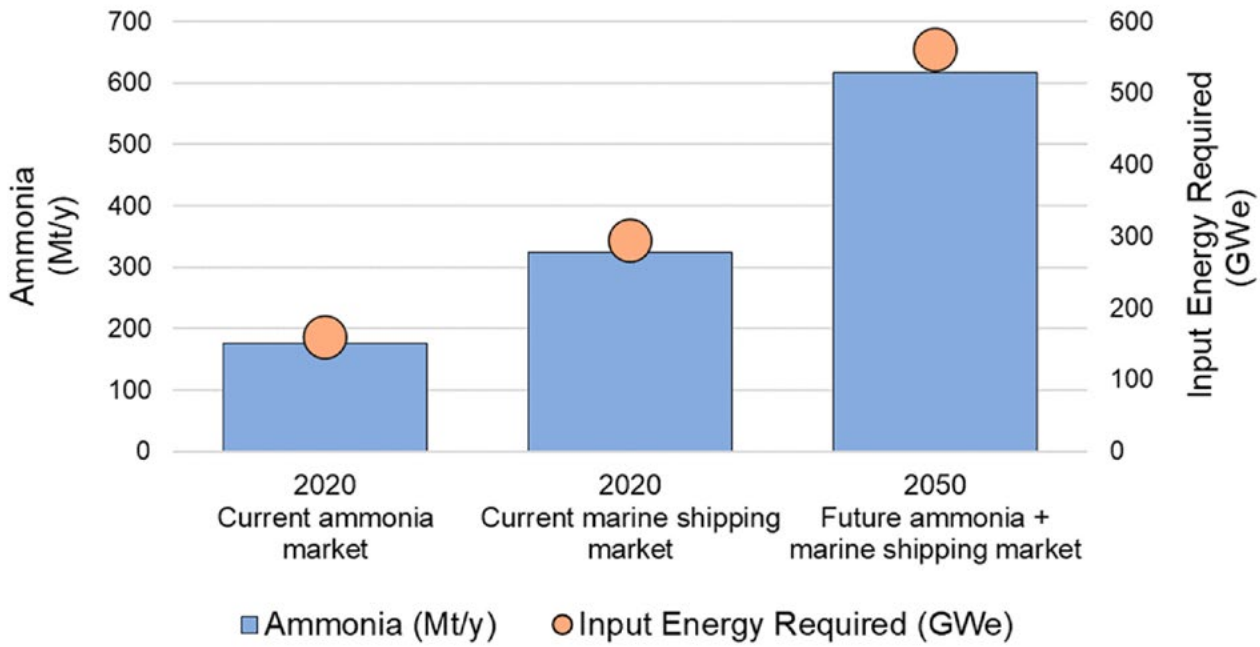
Ammonia

Around 180 million tonnes of ammonia is manufactured and used per year worldwide. Much of the Ammonia is used in the fertilizer industry as the primary feedstock for nitrogen fertilizer which, for its part, enables the higher yields we get from modern agriculture. Today, the ammonia industry is critical for the survival of human civilization.

Ammonia is made from hydrogen and nitrogen, and hydrogen is mainly separated from fossil fuels, causing emissions. Almost 180 GWe of electricity production capacity would be required to make the needed hydrogen with electrolysis, running 24/7. Therefore, the current fossil-fuel-based market for ammonia represents a significant and already existing market for a clean substitute.

The second large market for ammonia is its potential to replace fossil fuels in marine shipping. Current ship engines can be modified to operate with ammonia, and the shipping industry is already seeing ammonia as a potential pathway to decarbonize their activities. If the current shipping were fueled by ammonia, we would need over 300 million tonnes of ammonia (~300 GWe of power production), almost double the current ammonia market.

By 2050, both markets will grow substantially. As shown in figure 17, the combined total addressable market for clean ammonia in 2050 is over 600 million tonnes per year, needing an input energy source run-



ning at over 550 GWe, 24/7, which is more than the current global nuclear fleet.

Figure 17: The current and future potential ammonia markets in current uses and global marine shipping. Image credit: Lucid Catalyst

If we started building the required FNPPs in 2025 and did so at a constant rate until 2050, we would need to manufacture 24 GWe worth of vessels per year. Depending on the capacity of each ship, this would mean perhaps 25 to 50 FNPPs built each year just to meet the future ammonia demand for global shipping and current uses for ammonia. This is an estimate of the total addressable market, as it is not likely that all ships will convert to ammonia.

Desalination and District Heat

While the markets for desalinated water and district heat are geographically mostly different, they are discussed here due to the similarities in how they can be produced. Both can use hot water at 80-100 °C, made either with co-generation of heat and power, taken from the waste heat of electrolyzers, or both.

Most likely, these products will be co-produced with electricity, hydrogen, and other synthetic fuels. The market for heat or desalinated water mainly consists of coastal cities with either demand for district heating (mostly northern Europe/Baltic Sea area) or need for clean water (Southern Europe, Africa, and beyond). Especially the market for low-cost clean water is growing rapidly, and with climate change putting more pressure on both crops and people, this growth is unlikely to slow down. Clean water and flexible energy products would also be precious in any disaster zones where local infrastructure has been destroyed.

Jet Fuel

Many of us in the rich world have heard of “flight shaming,” perhaps even been affected by it. But most people are still just dreaming of long-distance traveling for vacation and possibly making plans to see that dream become a reality one day. Traveling for a holiday to learn about other cultures and customs, or even just to experience something new and relax, should not be the privilege of the wealthiest 10%.

Flight is a convenient and fast way to move people and goods long distances. Therefore, carbon-neutral jet fuel would be a handy and valuable commodity, especially if it is not much more expensive compared to jet fuel made from crude oil. While the very rich can afford to offset their flight emissions or buy tickets to first-class, the masses would rather travel cheaper, even if emissions and sustainability would matter to them.

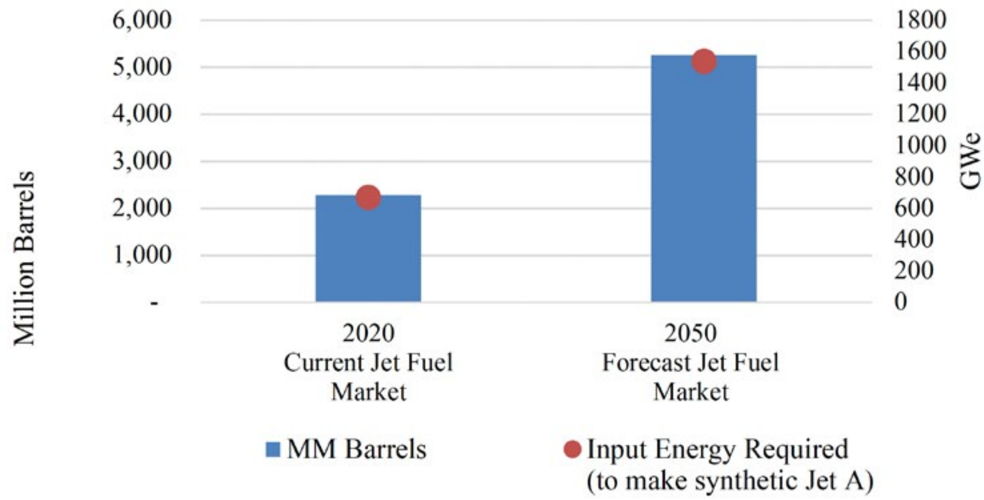


Figure 18: Jet fuel demand and forecast and energy required to produce it. Image credit: Lucid Catalyst

The world's commercial airlines used 95 billion gallons (2,262 million barrels) of jet fuel in 2019, according to Statista.[68] Due to COVID, that use almost halved to 52 billion gallons (1,238 million barrels) in 2020 and then rose to 57 billion gallons (1,357 million barrels) in 2021. Before the pandemic struck, aviation fuel use grew by almost 2 billion gallons per year on average between 2005 and 2019, growing by 40 % in total. On the other hand, the market for sustainable aviation fuels is estimated to grow from $72 million in 2020 to $6,262 million by 2030, having an impressive compound annual growth rate (CAGR) of 56.4%[69].

To recap the growth and numbers, it would take over 600 GWe, running 24/7, to produce the 2019 jet fuel usage with electricity. It will take over 1,600 GWe to meet the forecasted demand for jet fuel in 2050. If we started adding capacity in 2025, it would mean adding some 64 GWe each year.

68 https://www.statista.com/statistics/655057/fuel-consumption-of-airlines-worldwide/
69 https://www.prnewswire.com/news-releases/sustainable-aviation-fuel-market-to-reach-usd-6-261-9-million-by-2030--registering-a-cagr-of-56-4---valuates-reports-301378840.html

The emissions of European flights are included in the EU ETS already today. As ETS prices go up and the initial free allotment of emission credits runs out, the aviation companies will face pressure to increase ticket prices either due to more expensive clean fuel or increased emission costs. In 2019, Europe used 1.5 million barrels of jet fuel per day, roughly 550 million barrels per year.[70] A large 1.2 GWe FNPP can produce 4 million barrels of jet fuel per year, so today's total addressable market for just European jet fuel consumption is roughly 140 such vessels.

Synthetic Food

Food is an essential energy input for people, and how we produce the food and the many inputs food production takes matters a great deal. Agriculture's sensitivity to fossil fuel prices became apparent in 2021 as the nat-

70 https://www.statista.com/statistics/1242877/europe-oil-liquids-demand-by-fuel-type/

ural gas price spike drove the nitrogen fertilizer prices out of reach for many farmers[71]. This was amplified manifold by Russia's invasion of Ukraine, which threatens much of the global food supply, as both countries are important food producers. Suddenly, we were running low on both fertilizers for our crops, and grain imports from important "bread basked" countries.

The opportunity to produce ammonia without fossil fuels at low and stable costs was discussed previously. Similarly, we can make the chemicals, fuels, and other energy inputs for modern agriculture reliably with nuclear. But what about directly growing food in industrial-scale facilities, a bit like today's breweries?

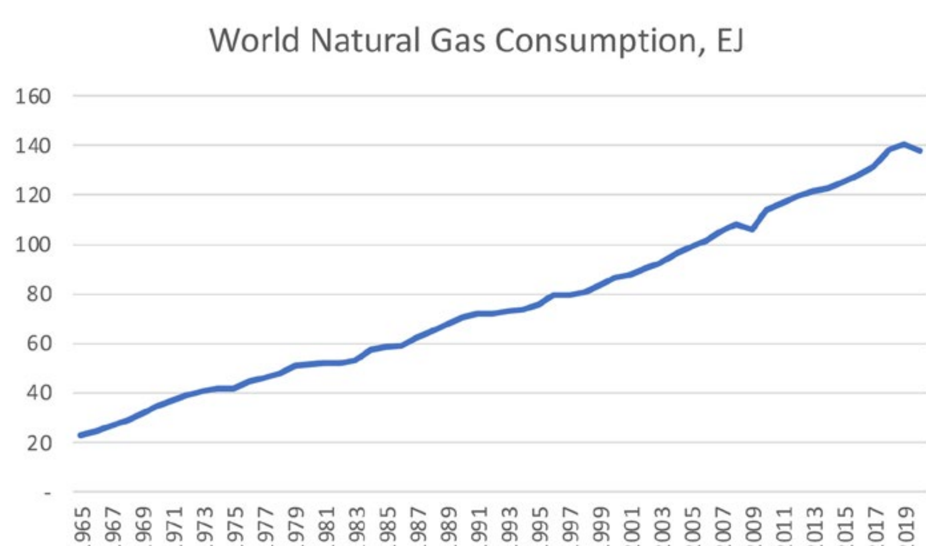
Many companies and research labs have researched and developed ways to make proteins from hydrogen and other inputs for the last ten years.[72] Such facilities are still expensive, but technology is evolving quickly. If production can be scaled up and a source for cheap and reliable energy input found, the prices of these new proteins might come down rapidly. At the same time, the pressure on animal agriculture keeps tightening from multiple angles, such as emissions mitigation and animal welfare concerns.

This kind of product would offer some significant emergency preparedness benefits as well. The global food cycle has multiple threats from multiple directions: climate change making yields more uncertain, geopolitics getting more volatile, fossil fuels getting more expensive, China hoarding the world's grain crops[73], or global logistics getting stuck for one reason or the other.

Having the capability of producing a significant part of national calorie- and nutrient intake independent of the weather or global supply chain situation has inherent value for the stability of a nation and the well-being of its people.

Methane, Methanol & Others

Besides the markets described above, there are significant markets for other chemicals and fuels if they can be produced at a relatively low cost. These include synthetic methane and methanol. Fossil methane (i.e., natural gas) is currently the third-largest energy source for humanity and growing rapidly. It is used in heating, cooking, industry, and power production but is also increasingly seen as an option for transportation like heavy long-distance trucking. It is also an essential feedstock for valuable chemicals such as plastics and our most significant source of hydrogen. Therefore, current hydrogen should be first replaced with clean hydrogen, and other natural gas use cases should be replaced with other energy direct sources wherever pos-



71 Nitrogen fertilizer is made of ammonia, which is made of nitrogen and hydrogen – of which the latter is today mostly produced from natural gas.
72 Such as Solar Foods in Finland. https://solarfoods.fi/
73 See https://asia.nikkei.com/Spotlight/Datawatch/China-hoards-over-half-the-world-s-grain-pushing-up-global-prices

sible. It only makes sense to scale up synthetic methane production after that.

Figure 19: Global Natural gas consumption has been growing steadily. Source: BP energy statistics 2021

Nevertheless, the potential synthetic methane market is enormous. Many European homes and buildings use natural gas for heating and cooking and are connected to the broader gas network. While a small part of natural gas can be blended with hydrogen in the European gas networks, this part is likely in the single-digit percentages before the pipelines and appliances need to be upgraded. Biogas is another option, but its maximum scale is also in the single-digit percentages.

Replacing fossil methane with synthetic methane at the scales used for just heating & cooking in Europe would mean we would need to find a massive source of sustainable and low-cost carbon to make the methane. This is a genuinely hard problem for regions such as Europe, which significantly depend on natural gas for their energy needs. The power grids and other infrastructure are not currently capable of scaling up electricity use so that it could replace natural gas use.

Methanol is another widely used chemical. The current methanol industry has a production capacity of 110 million tonnes (138 billion liters). Its main uses are as a chemical feedstock and as energy/transportation fuel, and the industry generates $55 billion worth of economic activity each year. Most methanol originates from fossil fuels such as natural gas or coal, but biomass and waste are also used. Methanol demand has grown steadily at around 4.5% per year for the last five years[74]. Methanol can also be made into gasoline with the ExxonMobil MTG-process[75].

74 https://www.methanol.org/the-methanol-industry/
75 https://www.exxonmobilchemical.com/en/catalysts-and-technology-licensing/synthetic-fuels

Islands and Other Remote Locations

One prominent and perhaps most salient first market is producing energy products in markets not connected to large grids. These often rely on diesel generators operated with expensive imported fuel and have higher than average energy costs. The Greek archipelago, Malta, and the Canary Islands are potential European customers for an FNPP providing electricity, desalinated water, and other energy products. They would likely be prime candidates for a long-term purchasing agreement with full services and waste management included.

Emissions Reduction Opportunities

Any replacement of fossil fuel with a clean alternative reduces our overall emissions. Replacing coal with nuclear reduces emissions by roughly 1 million tons per 1 TWh of production[76]. Hence, **a 600MWe FNPP producing just electricity would avoid almost 5 Mtons of CO_2 annually when replacing coal production. If it replaced natural gas, some 2.5 Mtons of CO_2 would be avoided annually.**

The numbers get a bit more complicated when it comes to emissions reductions from replacing fuels. For every kilogram of clean hydrogen used to replace fossil-based hydrogen made from natural gas, 9.3 kg of CO_2 emissions are avoided, or 280 grams of CO_2 per kWh of hydrogen. **If we produce 1 TWh of clean hydrogen and use it to replace 1 TWh of hydrogen made from natural gas, we will avoid 0.28 Mtons of CO_2.**

As a rough rule of thumb, a 600 MWe FNPP can produce a bit below 4 TWh of hydrogen per year, depending on the process used. **So, one FNPP at 600 MWe producing hydrogen would avoid around one million tons of CO_2 emissions per year compared to the hydrogen produced from fossil fuels**[77]. In

76 +/- 20% depending on coal quality, coal plant efficiency and so forth.
77 See Robert Rapiers' article for the math: https://www.forbes.com/sites/rrapier/2020/06/06/estimating-the-carbon-footprint-of-hydrogen-pro-

addition, some of the energy lost in the conversion as waste heat might be used for water desalination or district heat, further avoiding emissions there.

Synthetic e-fuels such as ammonia, methane, methanol, or jet fuel incur further losses in converting electricity to fuel. Therefore, the emissions that one FNPP can avoid gets lower. As a rough ballpark estimate, the electricity to fuel conversion might lose around half of the energy in the process unless the waste heat is used for district heat or water desalination. The total efficiency depends on the end product as well. Ammonia is more efficient to produce than synthetic methane or methanol, which are more efficient than jet fuel. A 600 MWe FNPP can produce almost 5 TWh of electricity, which can be used to make 3.5 to 4 TWh of hydrogen.

Producing e-fuels from this hydrogen demands both power and heat to capture nitrogen or carbon dioxide and the synthesis process. To get the scale, we can assume we can produce 2.5 TWh of e-fuels with one 600 MWe FNPP[78]. Depending on where and how it is used and what fossil fuel it replaces, roughly 0.5 to 1.5 Mtons of CO_2 can be avoided yearly.

Replacing CHP / District Heating.

Many large (Helsinki, Espoo, Vantaa, Turku, Oulu) and medium-sized Finnish cities (Rauma, Pori, Vaasa, Kotka) are on the coast, so their district heating could be provided with an offshore or near-shore vessel. Given that most of Finland's electricity production emissions are from the same CHP power plants that also produce district heat, replacing these fossil fuel plants with nuclear would eliminate both the emissions from the power sector and emissions from district heat. If roughly two-thirds of both power and district heat done with fossil fuels could be replaced, it would add up to approximately a 7 Mton reduction per year.

duction/

78 This is a very rough estimate.

In the European context, the market is much larger and different. District heating is not common in mainland Europe, except in eastern and northern countries. Europe has some 400+ TWh of district heat usage per year (compared to 35 TWh in Finland), which means that roughly 13% of space heating in Europe is done with district heat. In recent years, there has been increasing interest in the potential for moving from gas boilers into district heating networks in Europe[79]. The 2021 energy crisis and the 2022 war have only amplified these voices, so there might be a growing demand for district heating energy in Europe in the coming decades.

Replacing Natural Gas (and Oil) in Heating

Natural gas heating in Europe uses roughly 1,200 TWh of energy per year (~42 % of all heating/cooling energy).[80] Assuming emissions of 200 gCO_2 / kWh of heat delivered, the total gas heating emissions in Europe come at around 240 million tons of CO_2 per year. This will need to be replaced by different means, such as:

- Improving insulation (will decrease overall energy use for heating and cooling but will only proceed at a certain pace, some buildings might not be suitable).
- Moving to heat pumps (will increase electricity and peak power demand, especially in cold periods when air-to-air heat pumps operate at low efficiency. Higher investment cost than electric heaters. Can also provide cooling in summer).
- Moving to electric heaters (will increase electricity and peak power demand, low installation cost for the household if fuses/local grid can manage the extra load).
- Shifting to district heating (where district heating infrastructure is available or can be built. This

79 See for example this 2019 report from Aalborg University: https://www.districtenergy.org/viewdocument/towards-a-decarbonised-heating-and

80 According to https://www.oxfordenergy.org/publications/decarbonisation-heat-europe-implications-natural-gas-demand/

will also require a low-carbon way of making the heat).

- Replacing fossil natural gas with synthetic methane and/or mix in some hydrogen gas (does not need new investments from households and can use current delivery infrastructure for methane).

There is also a substantial amount of oil heating in Europe. Oil is often delivered with a truck instead of pipelines, but the methods for replacing fossil oil are essentially the same as above.

The central problem with all of the options above except the last one (replacing natural gas with synthetic methane) is that it requires more or less significant investments from the owners and/or the city to build new infrastructure in areas already built. This means tearing up streets, upgrading or changing household heating, and upgrading local power grids. Synthetic methane is a" drop-in" fuel for the current infrastructure, which is a significant benefit.

The problem is, making synthetic methane is not cheap, incurs a lot of losses, and requires a source of carbon. To get a sense of the scale, if just half (~600 TWh) of Europe's natural gas usage for heating purposes were replaced with synthetic methane made at 50% overall efficiency (power-to-methane), it would take 1,200 TWh of clean electricity to make.

If done with nuclear, that would mean roughly 150 GWe of capacity, or almost one hundred 1.6 GWe EPR reactors, which are the largest in the world, and a similar capacity of electrolyzers and other facilities. With wind, these capacities would need to be doubled or more. There would also need to be significant storage facilities, as natural gas use has a substantial peak in cold weather. The storage would need to be even larger if wind power was used. Solar would require even larger storage, as most of its production happens in the warm months of the year while gas demand is highest in the winter.

Replacing Liquid Transportation and Heavy Machinery Fuels

Road transportation is shifting into electric power trains from the current internal combustion engines. However, this shift will take time as it has a lot of bottlenecks to overcome. Nonetheless, parts of our logistics and heavy machinery can't be so readily electrified, so liquid fuels will continue to have significant demand.

Overall, roughly two-thirds of road transportation fuel is used in personal vehicles, which can most readily be shifted to full EV or plug-in hybrid powertrains. One-third is used in (semi)trucks, buses, 2-wheelers, and other vehicles. Heavy machinery (tractors, combine harvesters, construction machinery, forestry machinery, etc.) also uses a lot of liquid fuels, as does aviation. Even with a heroic effort to electrify our cars, perhaps half of all liquid fuel use remains much harder to electrify directly. Some of these use cases might get directly electrified with time and further development. Still, given the bottlenecks in, for example, critical mineral supplies and manufacturing capacity, that might take well into the second half of this century. Hence, we should plan to electrify them indirectly through affordable synthetic fuels. Down the line, there will also be a need for other synthetic chemicals to replace the chemicals, fibers, and plastics we now produce from crude oil and natural gas.

Summary of Total Addressable Market and CO_2 Reductions

The total market for different clean energy products is enormous, as long as they are competitively priced compared to fossil fuels. As the price of 24/7 electricity goes down, the total addressable market for it and hydrogen and e-fuels grows exponentially. For clean hydrogen at 5 €/kg, the market is marginal and mainly set by portfolio standards and mandates and few percent of use. For hydrogen at 1.5 €/kg, the potential market is much larger, as then it starts to compete with hydrogen from natural gas, even without carbon price or carbon capture and storage. Hydrogen at less than 1 €/kg can be made into synthetic fuels competitive at least with high oil and gas prices, and e-fuels made from hydrogen costing closer to 0.5 €/kg can compete even with moderately priced fossil fuels.

Costs come down with standardization and mass production, so the path is clear: Let's start replacing the "low-hanging fruit" first, such as electricity, heat and desalinated water, hydrogen in current uses, ammonia in today's uses. Even these have a total market in the hundreds of gigawatts in Europe. We can then work our way to larger markets such as ammonia for marine shipping, synthetic jet fuel, and other e-fuels. Shipyard manufactured nuclear enables much lower costs and rapid scaling of production, unlocking a new step-change in emissions reductions.

This study has assumed that we mostly use low temperature electrolysis, PEM or alkaline, for the production of hydrogen. This technology is commercially available, but has a somewhat low electricity-to-hydrogen efficiency of around 65%. Nuclear energy enables the use of high temperature steam electrolysis (HTSE), which is becoming commercially available in the next couple of years. The electricity to hydrogen efficiency of HTSE is far superior, over 90%. With HTSE, 40+% more hydrogen can be produced with the same amount of electricity compared to PEM or alkaline, which also means much higher emissions reductions. The average efficiency used in this study has been around 75%.

The good thing about shipyard manufacturing is that the benefits of serial production start from the second unit. But first, we need to make the first one. What are the steps to do that?

Next Steps, Bottlenecks, and Policy Recommendations

"There seems to be a lot to do." - Interviewee

Given the nature of the opportunity – creating a whole new industrial sector for Finland that also involves heavily political nuclear technology – it is likely that the Finnish government would be involved in multiple ways. First, there is the political permission in proceeding on a path like this, both informal in communications and more formal through the needed legislative and regulatory reform done with proper resources, priority, and alacrity.

Political acceptance improves (or decreases) in lockstep with public support and the industry's interest in making investments. These are interdependent and often show a "chicken and egg" -problem. It is hard to get politicians and officials at ministries to take something new seriously and get excited about it before the industry puts money where their mouth is.

But it is risky for the industry to invest significant sums into something that can quickly be canceled or brushed aside with a couple of sentences from a key minister or government official or something that faces considerable regulatory uncertainty from STUK. Public acceptance needs to improve further, and the media and broader public need to be informed of the potential and possibilities. Yet this needs to be done responsibly and carefully. Nuclear technology has many opponents who would like to see every project fail and who will make their best effort to make that happen.

Initial Steps

There was significant interest from multiple parties interviewed for this study to move forward with the idea of shipyard manufactured nuclear power plants in Finland. One of the potential first steps is to create and fund a project development organization that can:

- Do a deeper, more careful techno-economic assessment.
- Build the initial cooperative networks,
- Find suitable reactor technology providers and other partners to sign MoUs with, and
- Start communicating with stakeholders such as politicians, ministry officials, STUK, the public, and potential customers.

A conceptual design of a ship needs to be made, and for that, key information from the reactor technology provider(s) is required, so formal partnerships or MoUs are necessary.

This is already a lot of work, but perhaps not as much as one might think. From the interviews, a consensus emerged that the first serious steps into this would take roughly 20 people and two years, give or take. The total expense would likely stay below €5 million, but this naturally depends on the extent of the work included. Compared to the potential, this seems reasonable, and it should be possible to apply for public funding for some of the expenses. This does not include most of the licensing work needed, as it depends on the state of legislation and STUK regulations.

The initial stage of the project would need experts from the many fields in nuclear reactor and safety design, nuclear and safety licensing and permitting and validation, shipyard manufacturing and design, public and private financing, nuclear operations, public relations and lobbying, legislation, regulation, project management, and so forth.

At later stages, much more work is needed. Nuclear and maritime regulations become essential when planning the potential siting of the first power plant. Spent fuel management plans need to be drawn and submitted, political decision-in-principle applied for, and the required environmental impact assessments made. Further, as manufacturing hydrogen and e-fuels enters the picture, expertise and technology from these fields are needed, and possible regulatory hurdles need to be overcome.

Components and materials need to be tested and validated, the supply chain needs to be built, customers need to be acquired, licenses applied for, safety analysis carried out with regulators, and so forth. Financing for all this needs to be secured, so a lot also depends on whether these types of projects can be included in the EU Taxonomy (still unclear at the time of writing) and whether they can apply for government grants meant for energy pilot projects.

The first FNPP will carry much of the risks and costs, but luckily a significant part of these costs are "one time," and subsequent vessels can be manufactured at much lower costs. Typically, shipyard projects take roughly three years from start to finish, and for example, final systems testing takes a few months. Especially for the FOAK plant, these timelines will likely be stretched from the beginning, the middle, and the end.

In the political and legislative context, we might want to rethink how we view exporting nuclear energy as a service. Today, Finland cannot take spent fuel from a nuclear plant other than those in Finland. Yet we are leading the world in long-term spent fuel management.

We know, and have regulations and oversight in place to ensure, that storing spent fuel is exceptionally safe and has a minimal environmental footprint. Due to the political hotness of the topic elsewhere, this might be a very valuable service we could offer to potential customers. The risk-reward seems exceptionally favorable and could help Finland significantly in our medium to long-term economic future.

A lot depends on the regulatory demands, both for the timeline and overall feasibility. If STUK says that the whole ship needs to be "nuclear grade" instead of just the nuclear systems, it immediately kills the entire idea (at least for Finland). Anything "nuclear grade," due to the amount of paperwork and validation required, is easily ten times more expensive than regular high-quality industry-standard materials and components.

Yet, given that it is so hard and expensive to get anything new licensed as nuclear grade, the other industries, such as oil and gas, have caught up and even surpassed the quality of "nuclear grade." Thanks to standardization and successful incentivizing quality improvements, they have done so at a fraction of the cost.

Western regulations, regulators, and legislation have made innovation and progress very slow, complicated, and expensive in the last few decades. It is no wonder that many new nuclear companies have gone into other markets to innovate in. Many experts in the western nuclear industry see this as risky and problematic. Still, it is also true that we have made disruptive innovation in the nuclear field practically impossible in the west. And if innovation is needed and called for, it will happen somewhere. It is quite possible that moving this innovation to less experienced and less prescriptive regulatory regimes in South-East Asia will not be the best thing to happen for nuclear safety and public image overall. But it is happening nonetheless.

How can we change our thinking and regulatory frameworks in the west to allow and even encourage disruptive innovation in nuclear energy? It is certainly needed. It could add significantly to nuclear safety overall and help us mitigate the risks of worsening climate change, not to mention adding to the energy security and preparedness of many nations. The opportunity is enormous, both economically and ecologically. It needs to be done, and someone will do it. Why not us?

Finland is uniquely positioned to kickstart a new industrial sector of building and operating floating nuclear power plants at its shipyards. Effective design and manufacturing at shipyards can significantly reduce the cost of reliable low-carbon energy production while offering a tremendous opportunity for exports. Finland has many necessary pieces in place, giving us an advantage over other western countries. Finnish shipyards could build new clean and reliable energy at the gigawatt-scale, each year, and do it below half the cost of on-land nuclear plants.

This study lays out what are the opportunities and bottlenecks, and hopes to start a serious political and business discussion on whether Finland can and should be at the forefront of an enormous clean energy opportunity.

This study was commissioned by The Ecomodernist Society of Finland.
The study was carried out by Think Atom Ltd. Author: Rauli Partanen
https://ekomodernismi.fi/ | https://thinkatom.net/