Research for a better future

Digital Systems Sector

11 Nov 2022

Introduction to Small Modular Reactors (SMRs)

Tomas Eric Nordlander

SMR Technology Overview

Image from: CBC

What is an SMR?

- A Small Modular Reactor is a nuclear reactor with a power output of 10-300 MWe [*OECD Nuclear Energy Agency*].
- SMRs are often integral and modular, typically designed for factory fabrication, taking advantage of the benefits of the economies of series, and to be transported and assembled on-site, resulting in shorter construction times.
- These are some of the key elements for SMR competitiveness.
- There are currently over 70 SMR designs in development worldwide.

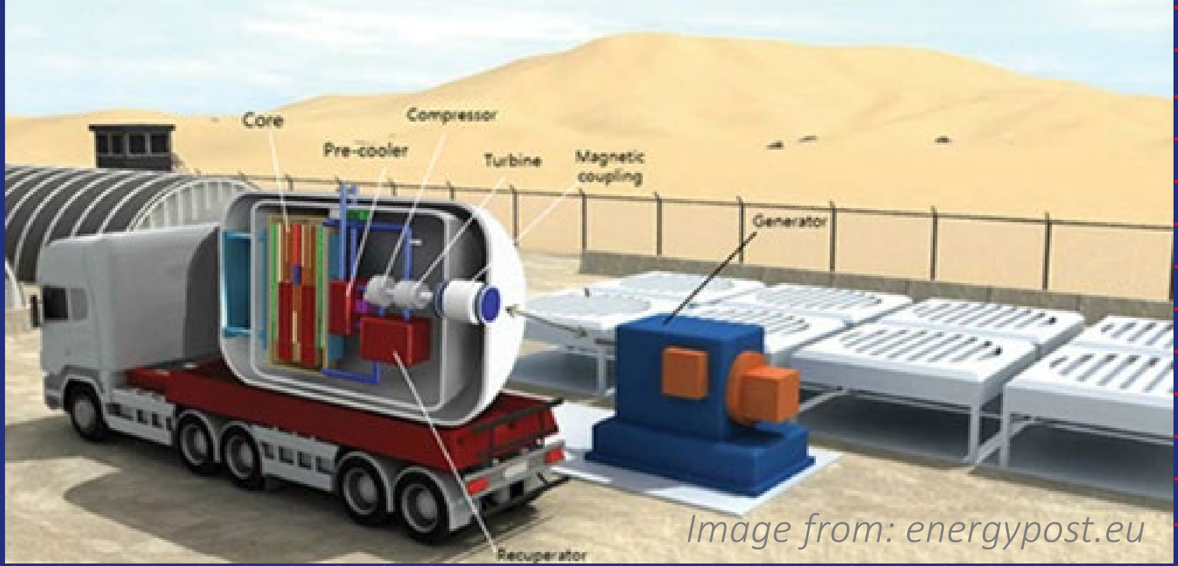


Image from: energypost.eu

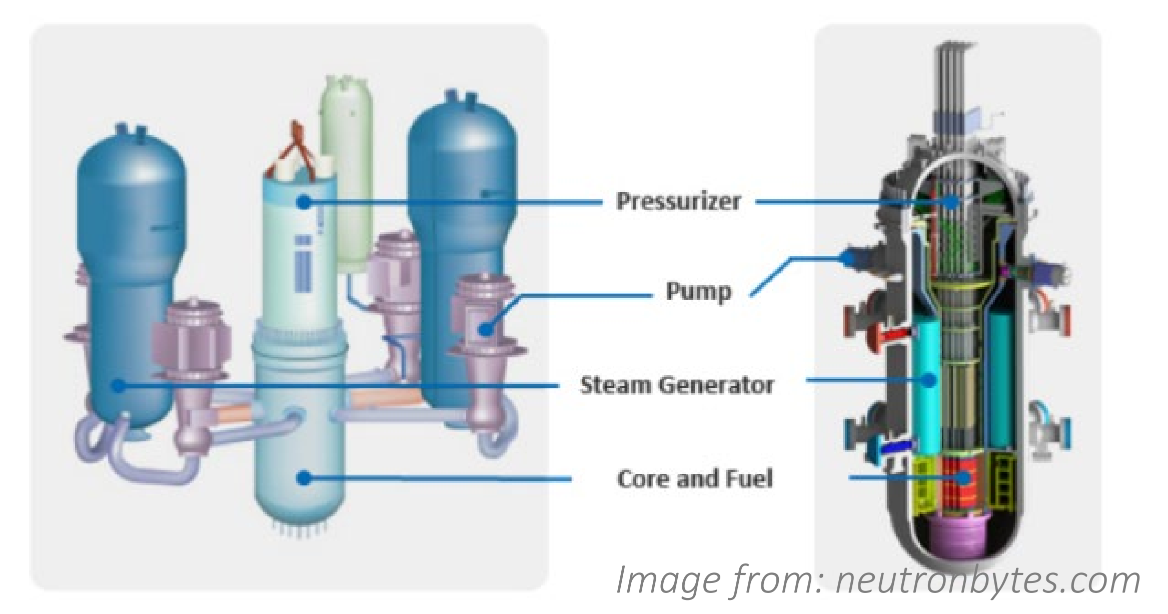


Image from: neutronbytes.com

Size comparison of SMRs

- Conventional Nuclear Power Plant
  - Power output of 700-1400 MWe
  - Used primarily for baseload electricity production and some hydrogen production
- Small Modular Reactor
  - Power output of 10-300 MWe
  - Can be used for electricity generation, district heating, sea water desalination, hydrogen production, etc.
- Micro Reactor
  - Power output of < 10 MWe
  - Typically used for space rocket propulsion, space craft power supply, power supply for remote towns, and provision of emergency power after natural disasters

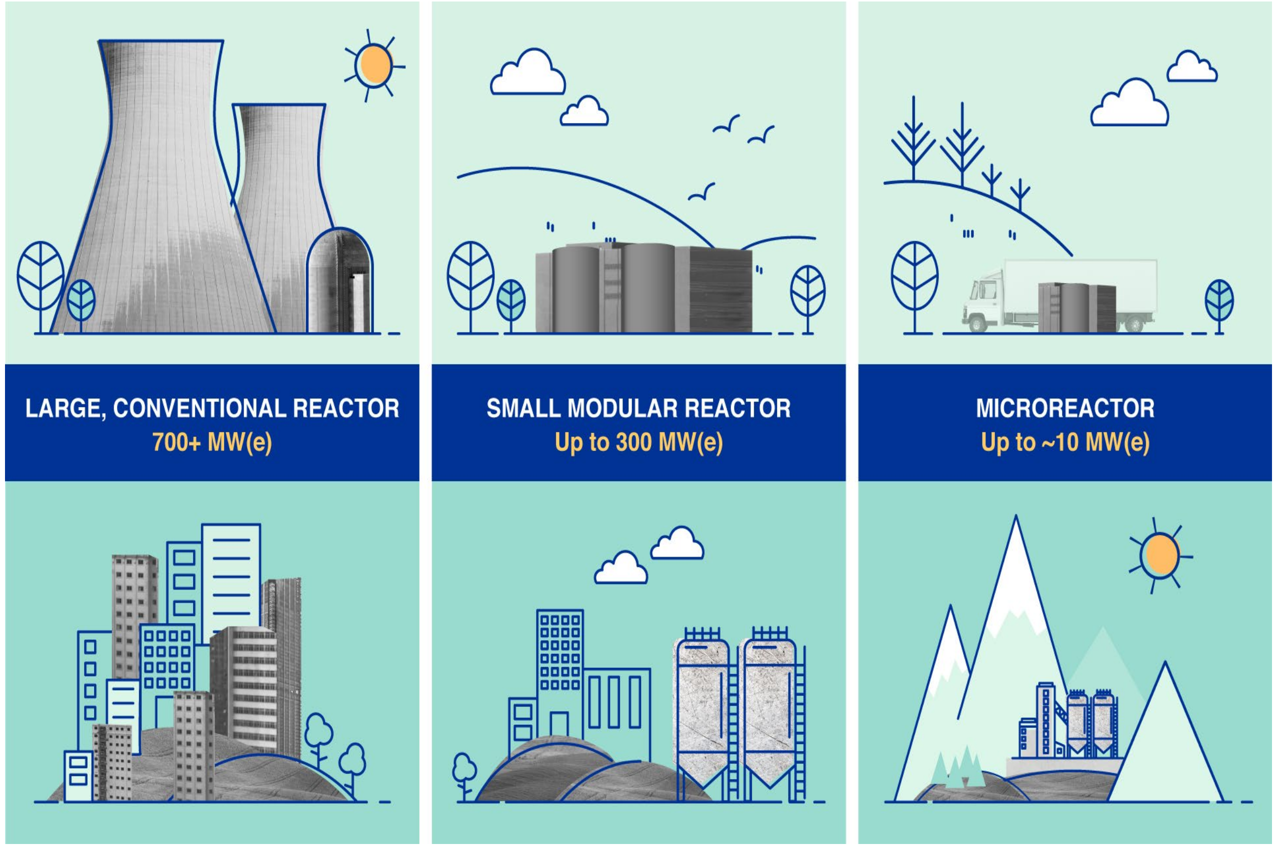


Image from: IAEA

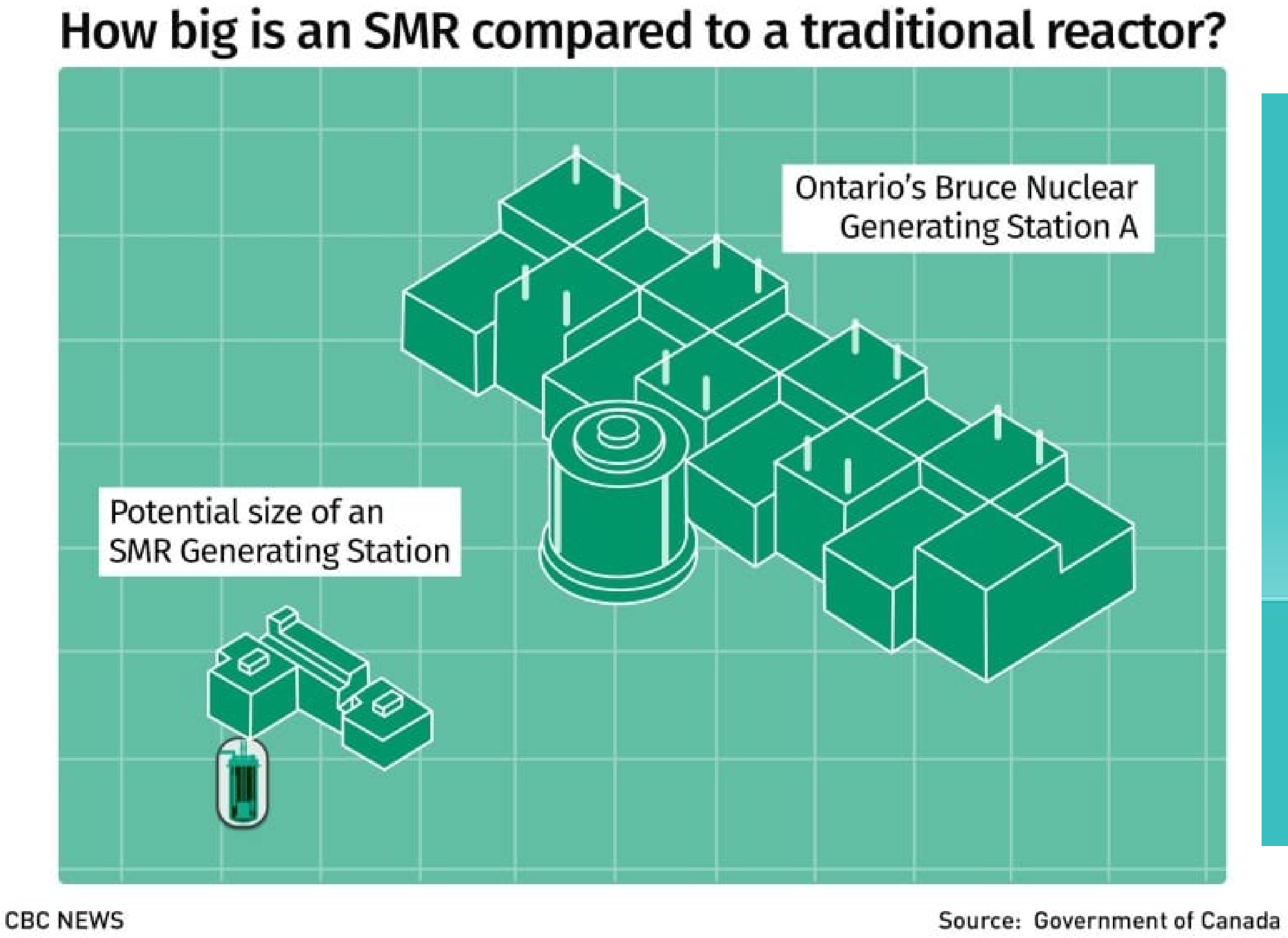
Comparing the SMR to the conventional model

Small Modular Reactor

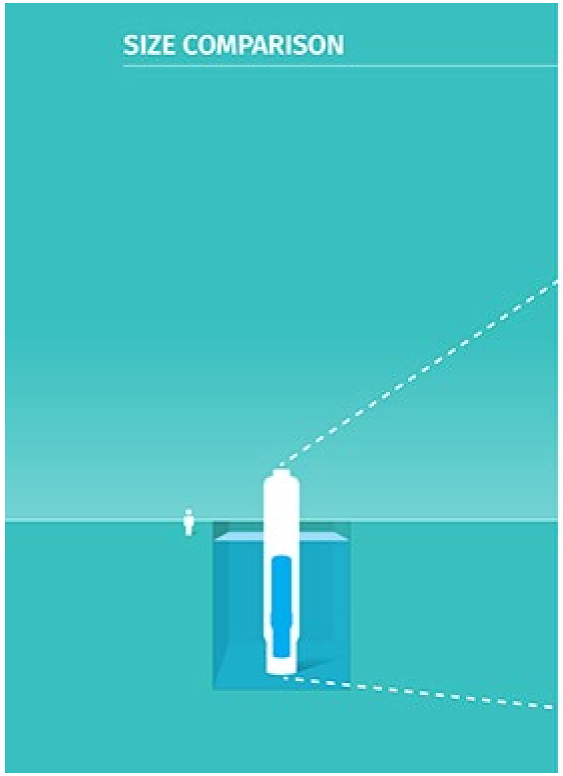
- Electrical output per unit 10-300 Mwe
- Modular design built in factory and last 10% assembled on site
- Site footprint 195 Mwe ≈ 7 hectare/17 acres
- Potential uses: electricity generation, hydrogen production district heating, desalination
- Safety Systems: Passive, inherent negative reactivity feedback
- Scalable: the ability to add additional units to the site based on growth and needs
- Load following capability

Conventional Design

- Electrical output per unit 700-1400MWe
- Some modular design but 70 -80% constructed onsite
- Site footprint 1000 Mwe ≈ 259 hectare/640 acres
- Potential uses: electricity generation, hydrogen production
- Safety Systems: Active systems requiring electrical power
- Normally the site is designed for 1 to 2 units due to size
- Normally used for base load



SMR



Conventional reactor

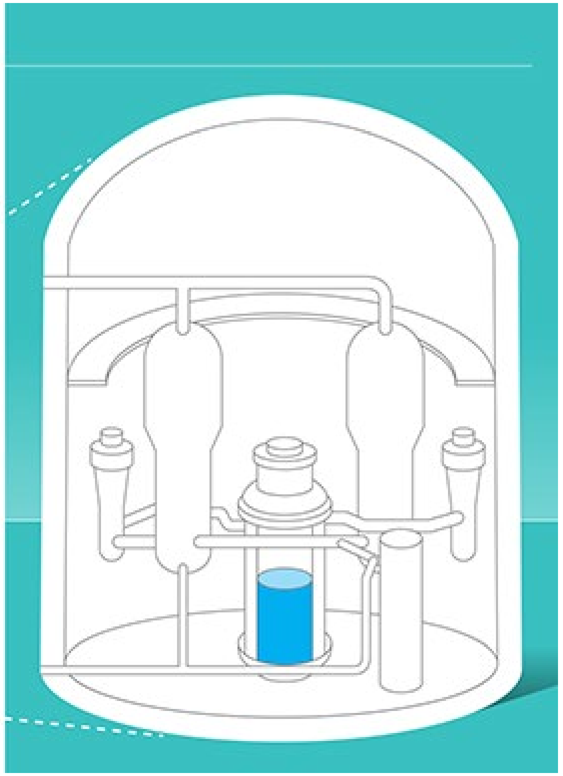


Image from ansto.gov.au

There are 70+ SMRs currently in development

- SMR design types
  - Water-cooled, including:
    - Light water reactor (LWR)
    - Heavy water reactor (HWR)
    - Pressurized water reactor (PWR)
    - Boiling water reactor (BWR)
  - High temperature gas cooled (HGTR), including:
    - Pebble bed reactor (PBR)
  - Fast neutron, including:
    - Liquid metal fast reactor (LMFR)
    - Gas modular fast reactor (GMFR)
  - Molten salt, including:
    - Chloride salt cooled reactor
    - Fluoride salt cooled reactor

- Major SMR manufacturers
  - Seaborg (Denmark)
  - NuScale (USA)
  - Southern Company / TerraPower (USA)
  - X-energy (USA)
  - TerraPower (USA)
  - Holtec (USA)
  - Terrestrial Energy (Canada)
  - Rolls-Royce (UK)
  - Swedish Modular Reactors / Uniper

Current SMR Manufacturers Near-term Construction

- Southern Company / TerraPower technology (2026)
  - Molten Salt technology
  - 50kW demonstrator reactor
- Seaborg CMSR (2026)
  - Molten Salt technology
  - 200-800 MWe floating system
- GE Hitachi BWRX-300 (2028)
  - Boiling Water Reactor
  - 300 MWe
- NuScale Voygr (2029)
  - Pressurized Water Reactor
  - 77 MWe per unit, scalable from 4 to 12 units.
- TerraPower Natrium reactor (2029)
  - Molten Salt technology
  - 345 MWe Sodium Fast reactor

SMR Benefits for Society

Image from Oregon State University

European Commission

Supporting the Green Shift

- Nuclear is a zero-emission clean energy source
- Nuclear energy's land footprint is small
- Nuclear energy produces minimal waste
- "Nuclear is an essential complement to wind and solar power… for a more reliable, cleaner supply of electricity"

(Source: Nuclear Energy Institute)

- An important contributor to the EU goal to be climate-neutral by 2050!

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Why Europe Is Looking to Nuclear Power to Fuel a Green Future

MARK HIBBS

FEBRUARY 18, 2022
COMMENTARY
Source: Getty

To successfully cut carbon, Brussels needs a stopgap energy source.

European regulators recently proposed to include nuclear power and natural gas in a select group of energy sources, alongside renewables such as wind and solar power, to help reduce greenhouse gas emissions. This initiative follows the EU's commitments to multilateral climate diplomacy and the 2019 announcement of the Green Deal to make the EU economy carbon-neutral by 2050. The European Commission (EC) says it aims to facilitate new gas and nuclear investments for a "difficult transition" between now and mid-century, a period during which coal-burning must be phased out and electricity demand may dramatically increase.

Image: carnegieendowment.org

Supplement the existing (& future) power grid

- SMRs can supplement the existing green power grid through load following.
- During periods of low wind / solar / hydro power, SMR output can be increased to meet energy demands.
- In times of high renewable energy output, SMRs output can be reduced or redirected for other uses.

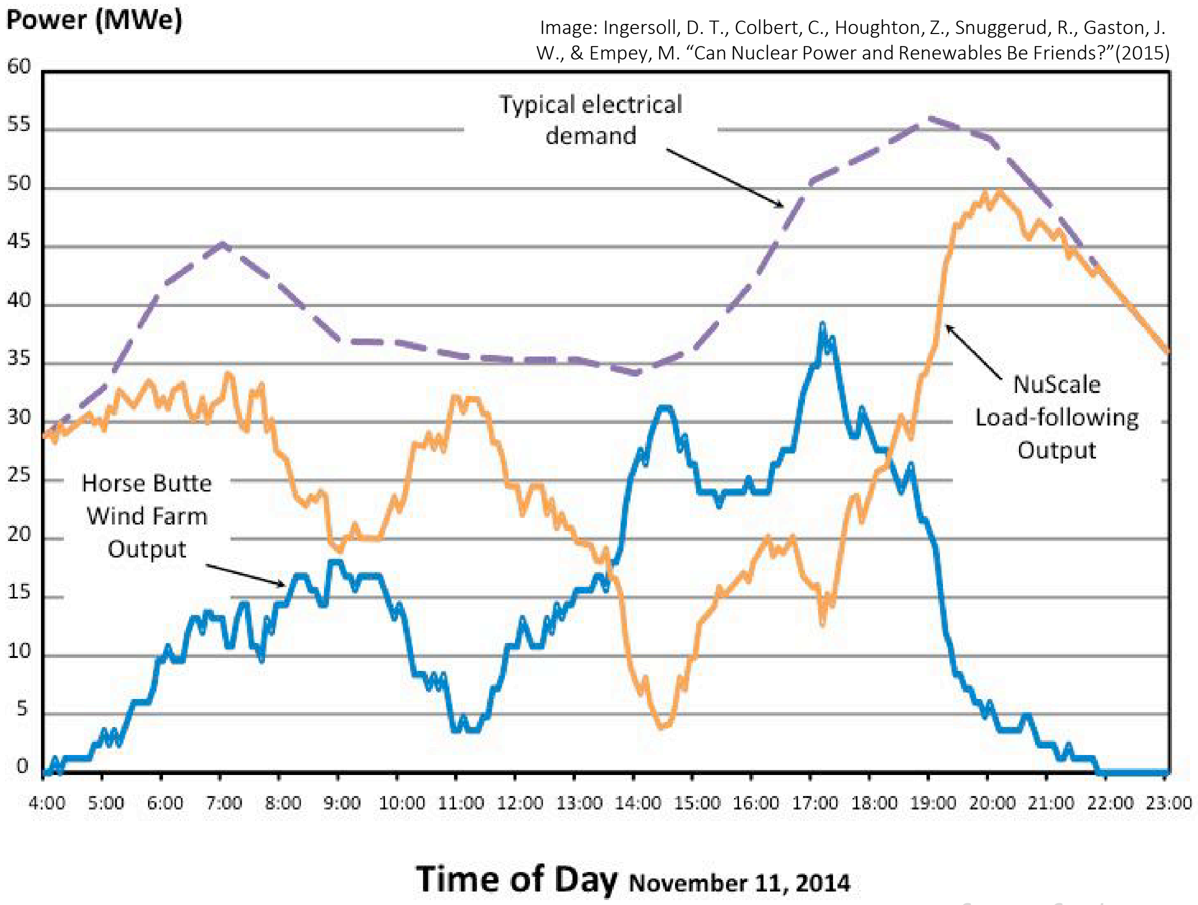
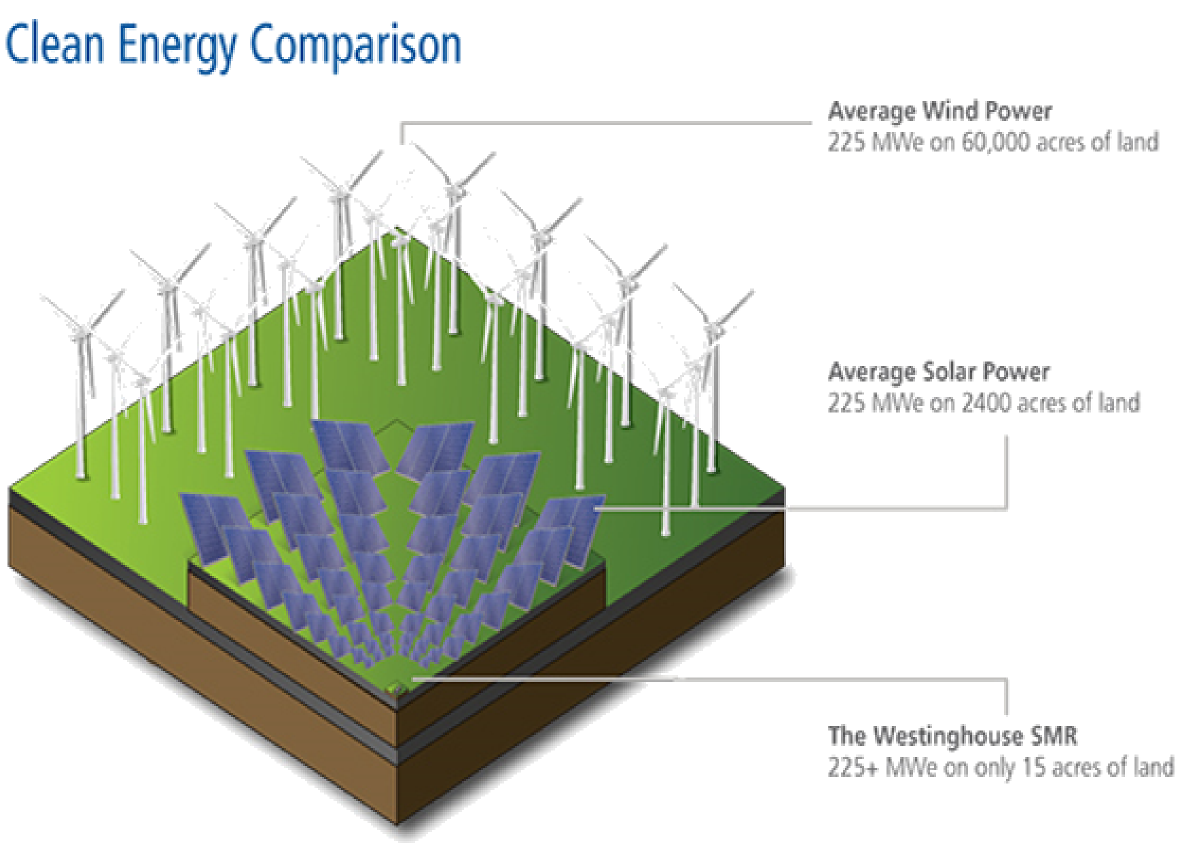


Image from forbes.com

Less space, more power

- SMRs take up significantly less land space than conventional nuclear power plants
- SMRs can provide significantly more power per acre of land than many renewable energy sources

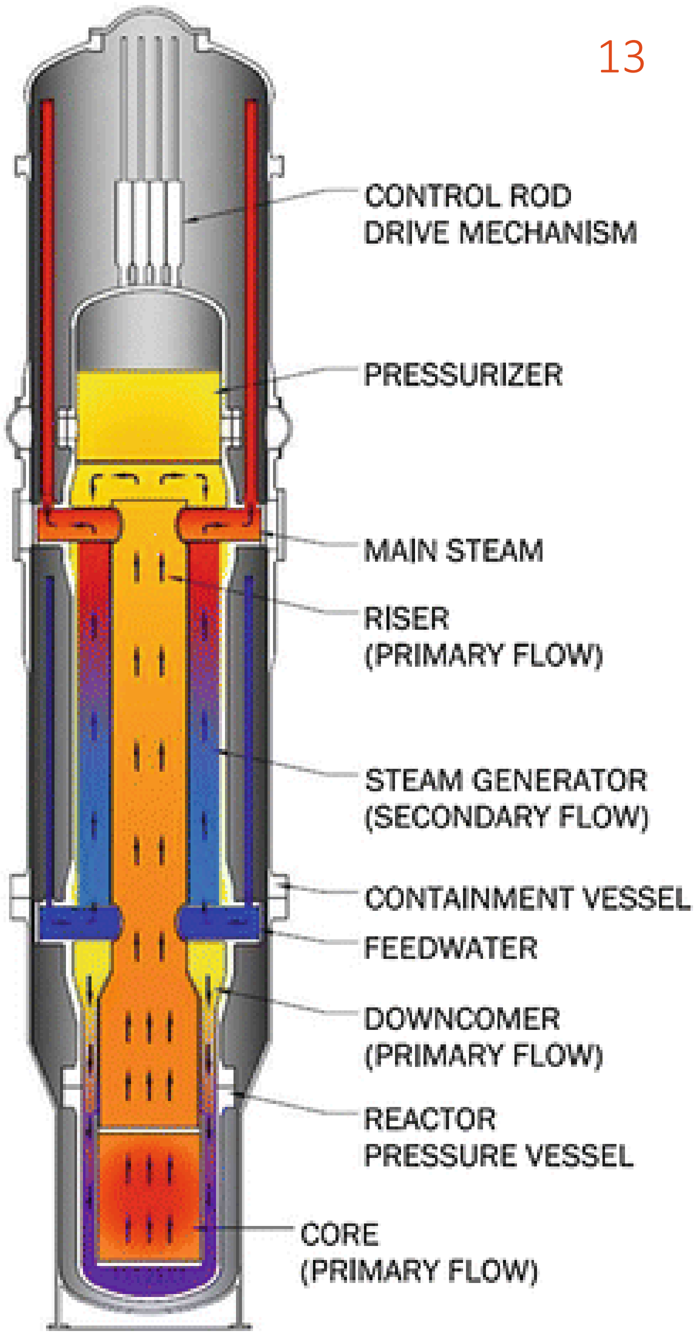
- For example, to generate 225+ MWe:
  - A wind farm needs approx. 60.000 acres (~242km^2)
  - A solar farm needs approx. 2.400 acres (~10km^2)
  - An SMR needs only approx. 15 acres (<1km^2)



Inherently safer design

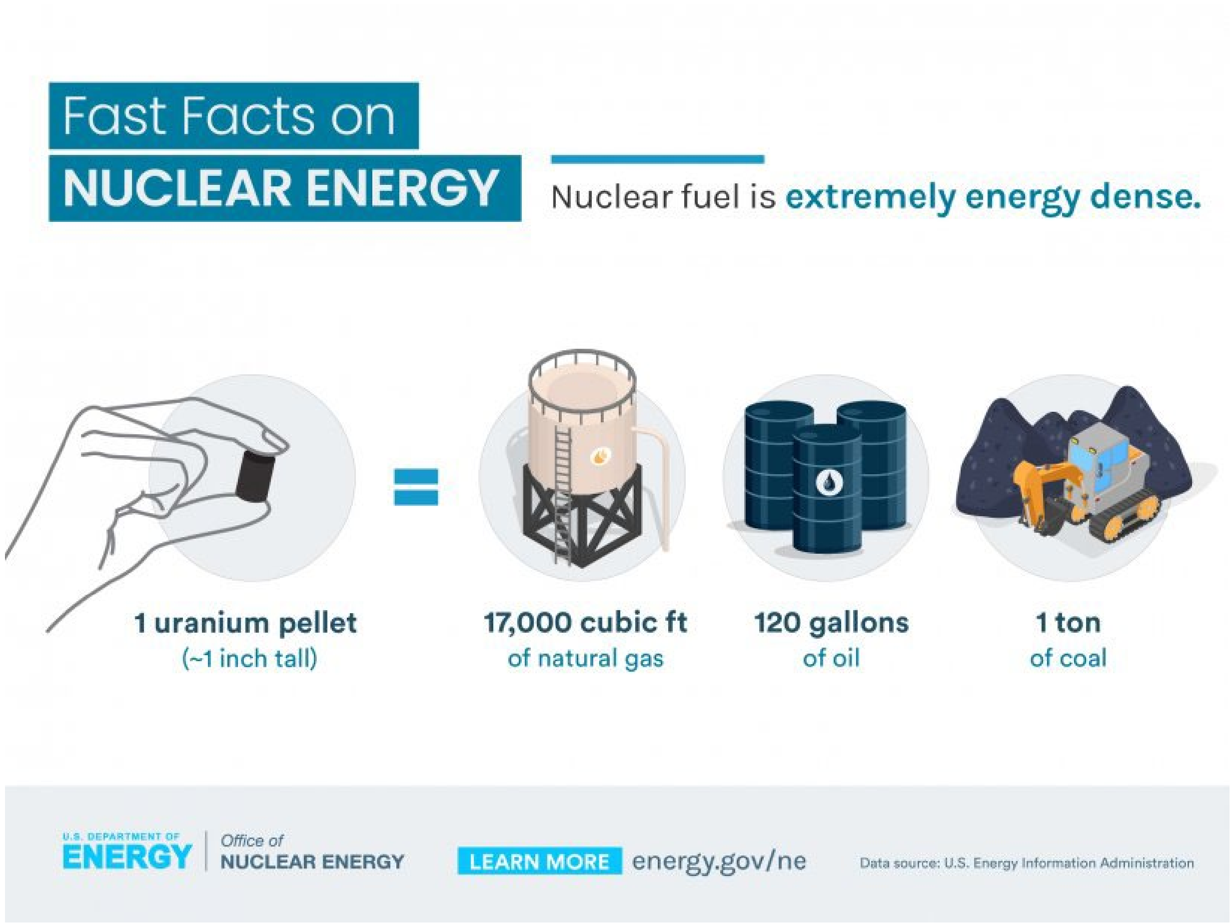
- SMRs use passive safety systems, which rely on the natural laws of physics to shut down and cool the reactor in abnormal conditions
  - Examples: gravity, differential pressure, natural heat convection

- Passive safety systems require no power source, and no human actions in order to initiate, so they are not affected if there is a loss of power, and the risk of human error is significantly reduced



Less nuclear waste

- The smaller core of the SMR means that it uses less nuclear fuel than a conventional plant, thus producing less waste
- SMRs require less frequent refueling (every 3-7 years vs. every 1-2 years for conventional plants)
- Some SMRs (e.g., molten salt) can recycle spent fuel from conventional plants.
- The smaller, inherent design of SMRs means less contaminated parts so overall the amount of nuclear waste generated by the SMR is significantly reduced.



SMR design allows for more flexible deployment

- Significantly smaller footprint means that SMRs can be built in areas where it would not have been possible to construct a conventional nuclear plant.

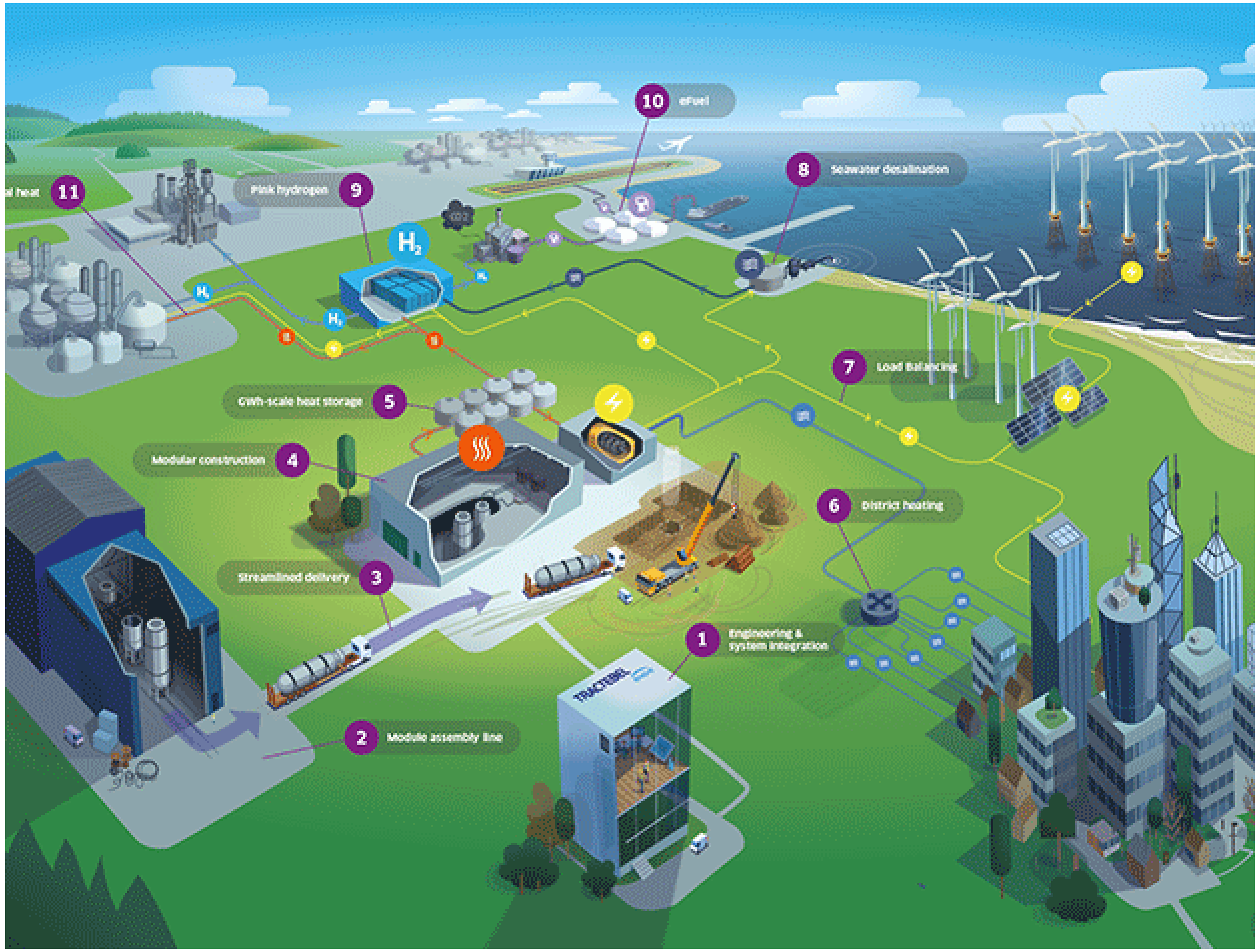


Image: tractebel-engie.com

Thorium fueled reactors

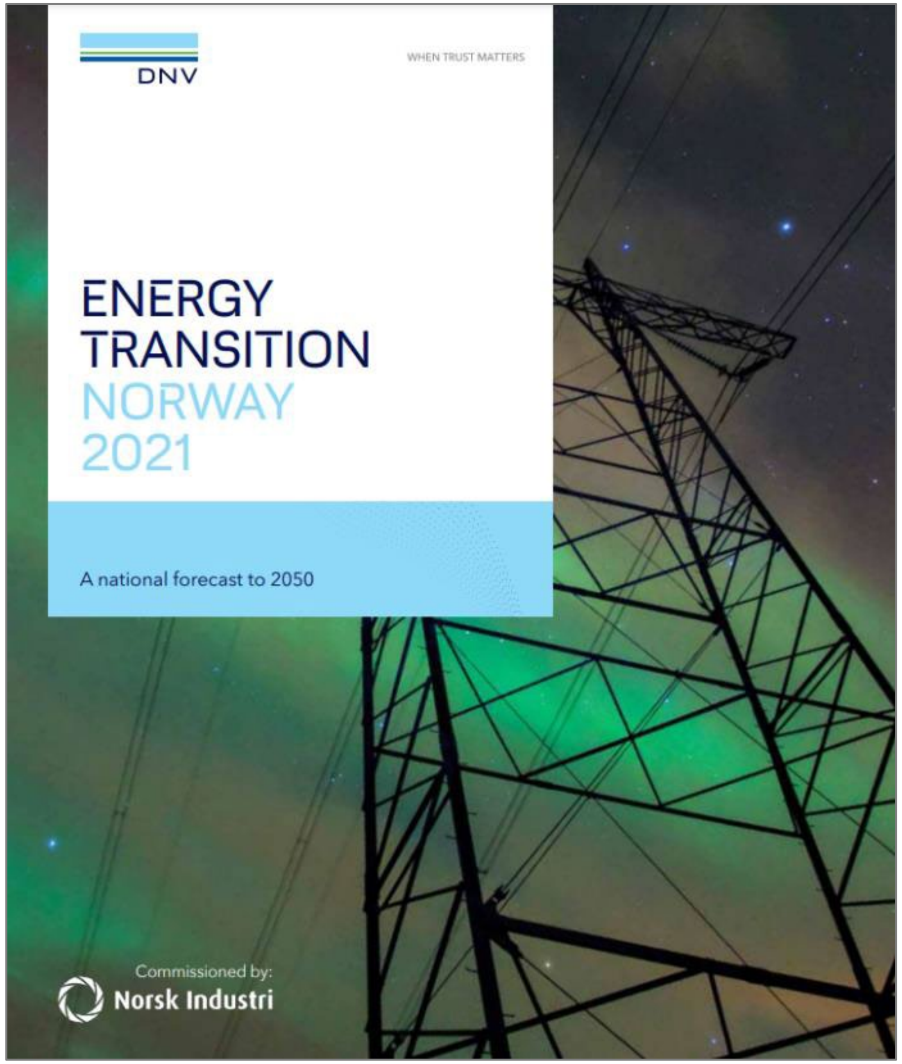
Advantages of Thorium over Uranium

- Much greater abundance found in the earth
- Superior physical and nuclear fuel properties
- Reduced nuclear waste production when used in a Molten Salt reactor
- Half-life of waste is significantly shorter (hundreds vs thousands)
- Low weaponization potential
- No enrichment needed for fuel grade use
- One ton Thorium produces the same energy as 200 tons Uranium and 3,500,000 tons of coal

Potential SMR use cases in Norway

The need for a stable electricity source

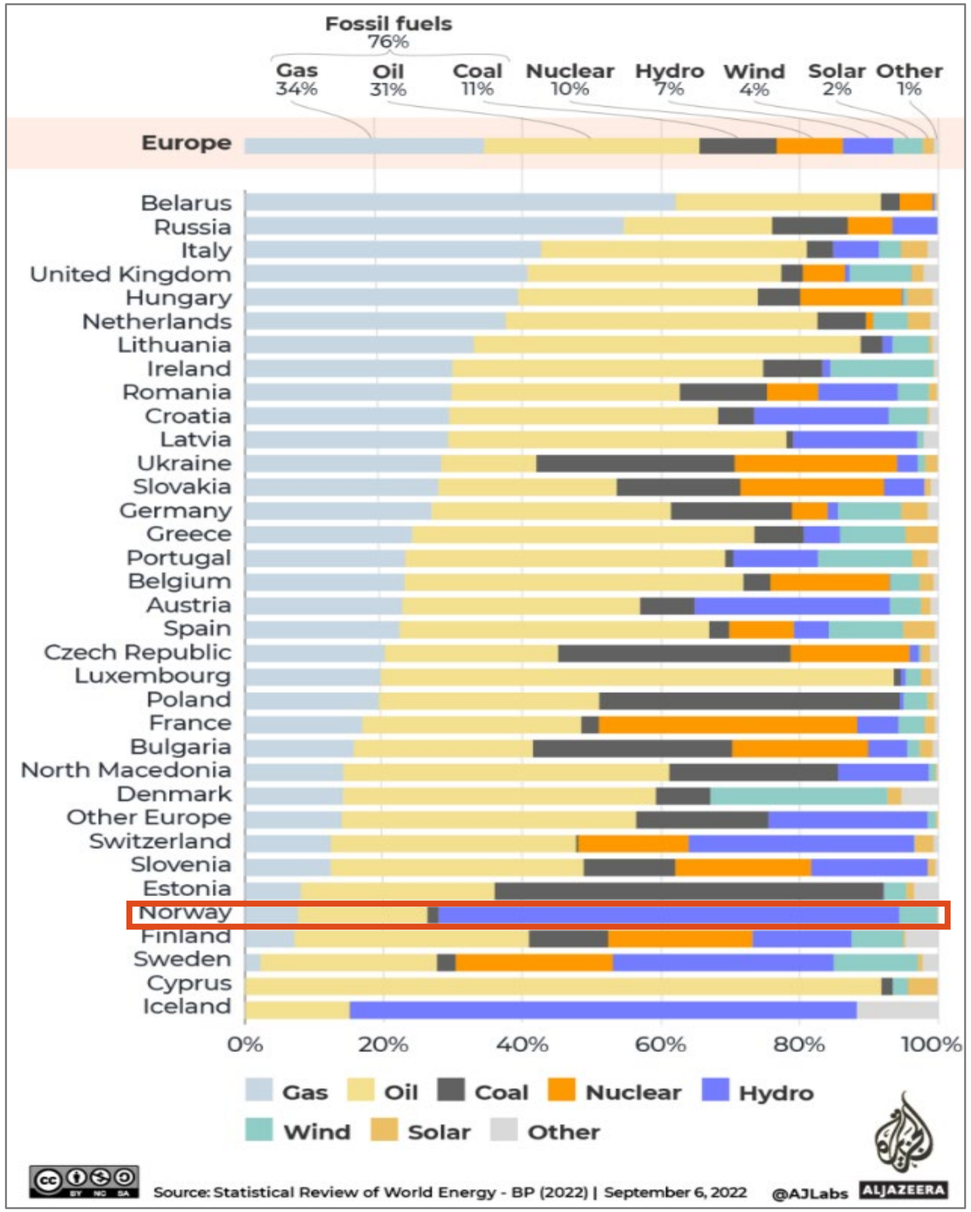
- The continued electrification of society will require stable, sustainable energy sources.
- Norway has set ambitious goals to reduce emissions by 55% by 2030 (compared to 1990 levels), and to reduce to 0% emissions by 2050.
- According to DNV's *Energy Transition Norway 2021* report, "Norway will most likely only achieve a 24% reduction by 2030 and a 79% reduction by 2050".
- In the meantime, demands for electricity continue to increase.



Why consider nuclear in Norway?

- Hydropower is still the primary electricity source in Norway today.
- Norway has invested a lot in hydrogen and battery technology in recent years.
- We are seeing a growing interest in utilizing nuclear in Norway in situations where it is either not feasible or not financially viable to replace fossil fuels with renewables, batteries or gaseous fuels.

Image: www.aljazeera.com



Potential use cases in Norway: Maritime

- Already a lot of interest from the Norwegian maritime sector:
  - NTNU “NuProShip” project
  - Ulstein Thor concept

- Nuclear is a zero-emission alternative to highly polluting marine gas oil.
- Zero-emission alternatives such as hydrogen or ammonia take up a lot of valuable space on board due to high fuel density.
- This renders them infeasible for use on the longer-duration ocean trips typical of fishing, merchant ships etc.

Maritim

NTNU vil utvikle atomdrevet framdriftssystem

Et NTNU-ledet prosjekt vil utvikle framdriftssystem basert på små kjernekraftreaktorer.

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Nuclear vessel 'could be floating charging station for electric cruise ships'

29 April 2022

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Norwegian shipbuilder Ulstein has launched the design concept for a replenishment, research and rescue vessel - referred to as *Thor* - that will feature a thorium molten salt reactor. It says the ship could be used as a mobile power/charging station for a new breed of battery-driven cruise ships.

The Thor concept design (Image: Ulstein)

The 149-metre-long vessel features helicopter pads, firefighting equipment, rescue booms, workboats, autonomous surface vehicles and airborne drones, cranes, laboratories and a lecture lounge.

Potential use cases in Norway: Remote locations

- The flexibility and significantly smaller footprint of SMRs means that they can be deployed in remote locations where it would not have been possible to build a conventional power plant.
- Norway’s mountainous geography is no longer a barrier to clean, sustainable and stable energy.
- SMRs can provide energy security to remote locations, such as islands and rural areas not currently connected to the national grid.
- SMRs can be used for both district heating as well as providing baseload production.

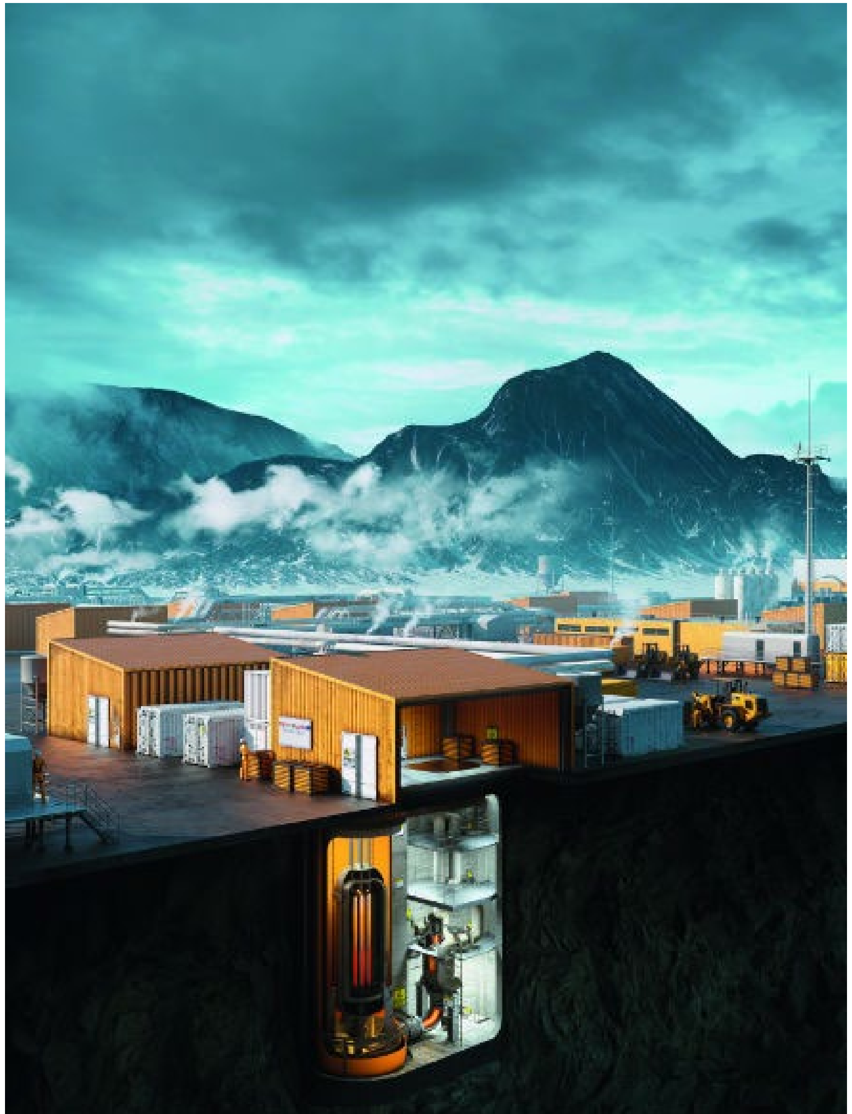
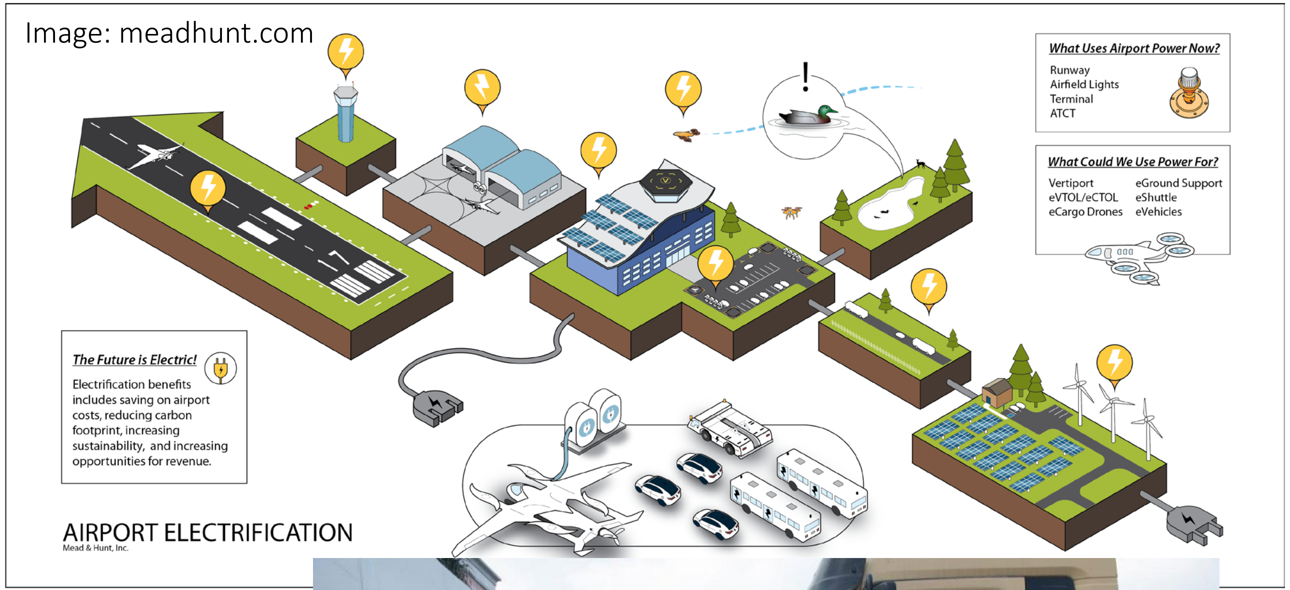


Image: www.modernpowersystems.com

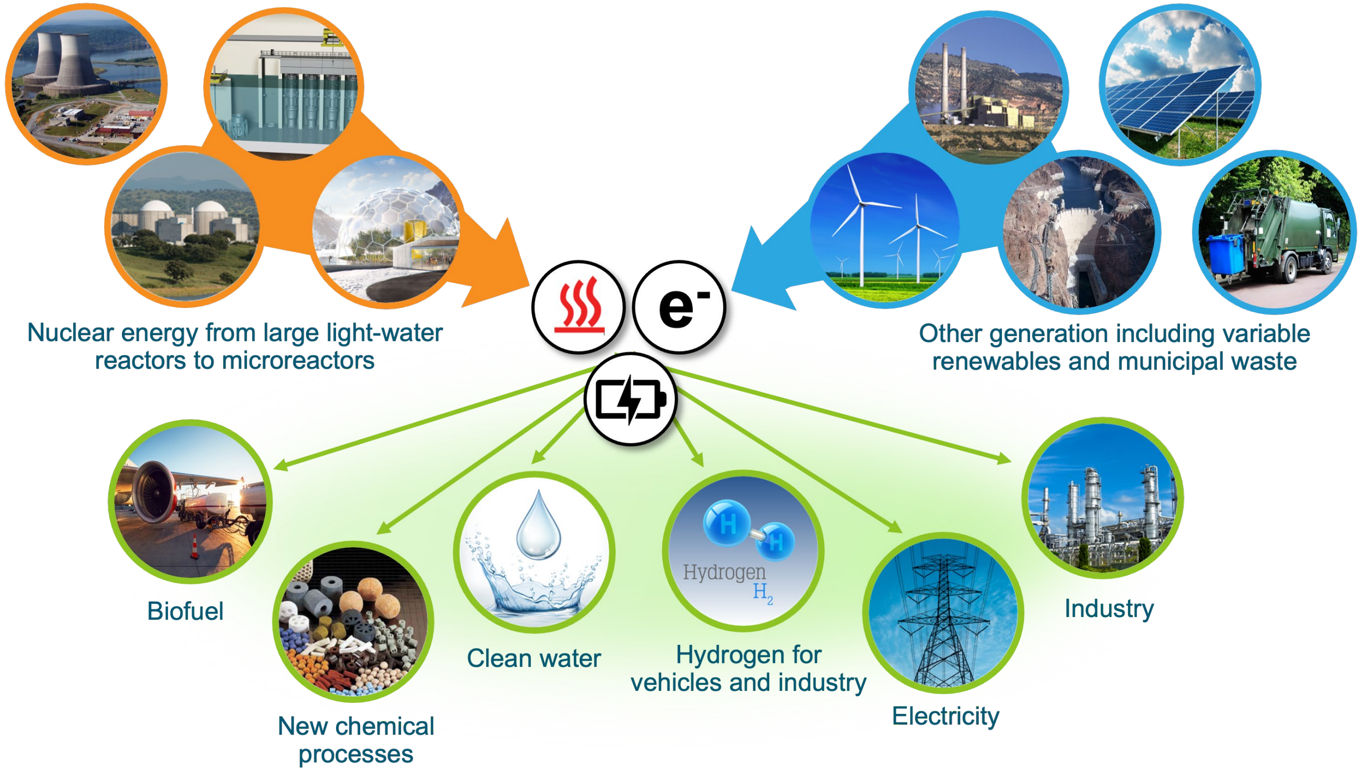
Potential use cases in Norway: Local electrification

- The move towards electrification of society creates greater demands for stable electricity sources.
- SMRs can be deployed at local levels to provide electricity to discrete areas without needing to pull energy from the national grid.
- Examples include: airports, factories, and large-scale vehicle charging stations, such as distribution depots.



Potential use cases in Norway: Integration

- SMRs can be integrated with other energy systems to provide energy security and stability.
- The heat from SMRs can be used for co-generation of e.g. hydrogen for industry.
- The load-following ability of SMRs can be utilized in times of low production from our renewable sources.



Conclusions

- There is increasing need for Norway to be able to produce secure and stable electricity for national consumption.
- SMRs offer flexibility and integration opportunities that should be investigated as part of the energy mix for the future.
- There are several attractive use cases in the immediate future for SMRs in Norway.

IFE – Norway’s nuclear experts

HALDEN PROJECT HTO

SMR research in the Halden HTO Project

- A research activity titled “Operation of Multiple SMRs” was initiated in 2018.
- In 2019, a basic principle iPWR control room simulator was installed in Halden.
- A first simulator study was carried out in 2019 with the goal to explore how one operator would monitor multiple (3) reactors at the same time, during four scenarios of increasing complexity.
- In 2022, IFE has received delivery of a full-scope iPWR simulator, capable of simulator up to 12 units operating in parallel and enabling experimental data collect for more complex and challenging scenarios.

Examples of Human Factors challenges

- Multi-unit operation
  - Operating several reactor units from a single control room; radical departure from conventional NPP
  - Challenges associated with multi-unit confusion, high workload, loss of situation awareness, confusing roles & responsibilities
  - IFE has experience with these challenges in other projects such as Avinor (remote tower) and Bane Nor (centralized traffic control)
- Remote operation
  - Monitoring and control of remotely located SMRs from a central location
  - Challenges associated with signal latency, higher levels of automation, situation awareness, operator familiarization and competence
  - IFE has experience with these challenges in other projects such as Equinor (multiple offshore unmanned platforms)

About the OECD NEA Halden Reactor /HTO Project

- The Halden Reactor Project (HRP) was established in 1958
  - Joint research programme: (i) nuclear fuels & materials (F&M), and (ii) Man Technology Organisation (MTO)
  - The oldest NEA (Nuclear Energy Agency) joint project & the longest-running nuclear research project in the world, renewed every 3 years since 1958
  - Operated by IFE, and supported by 100+ organisations in 20 countries worldwide
  - As part of the project IFE owned and operated:
    - The Halden Boiling Water Reactor (BWR)
    - The Halden MTO research labs, including the Halden Man Machine Lab (HAMMLAB)

  - The Halden reactor was shut down in June 2018, after 60 years of service
  - The HRP F&M program finishes with a final project in 2021-2023 .

  - The Halden Human Technology Organisation (HTO) was initiated in January 2021, supported by 20 organisations in 12 member countries. It is a direct continuation of the HRP MTO program.

Thank you!