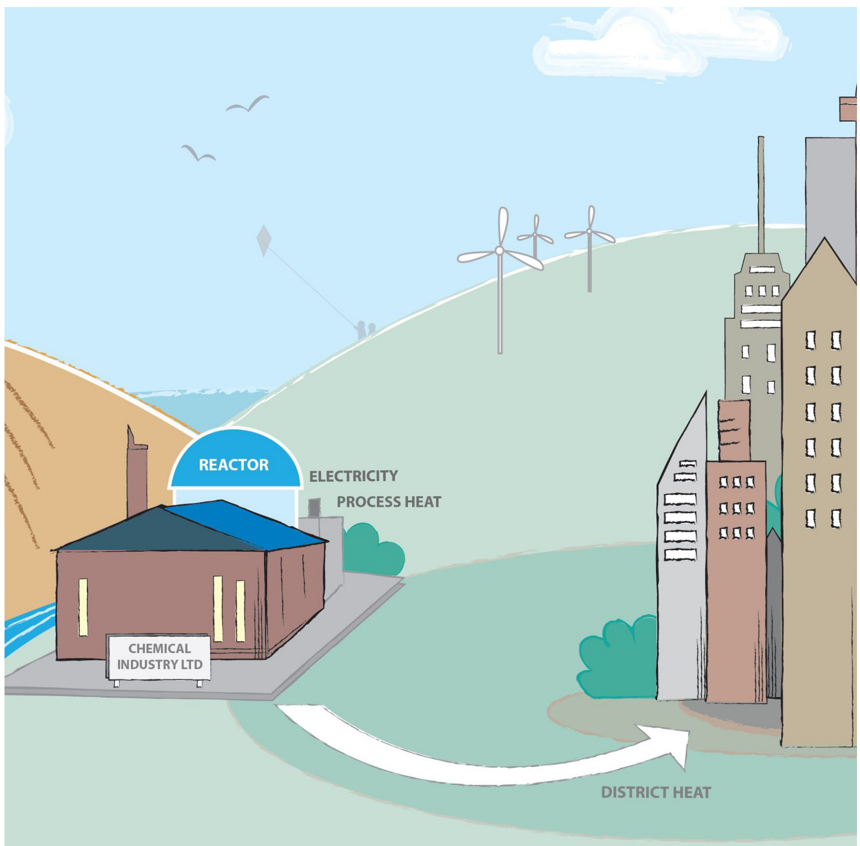
SMALL NUCLEAR REACTORS AND WHERE TO USE THEM



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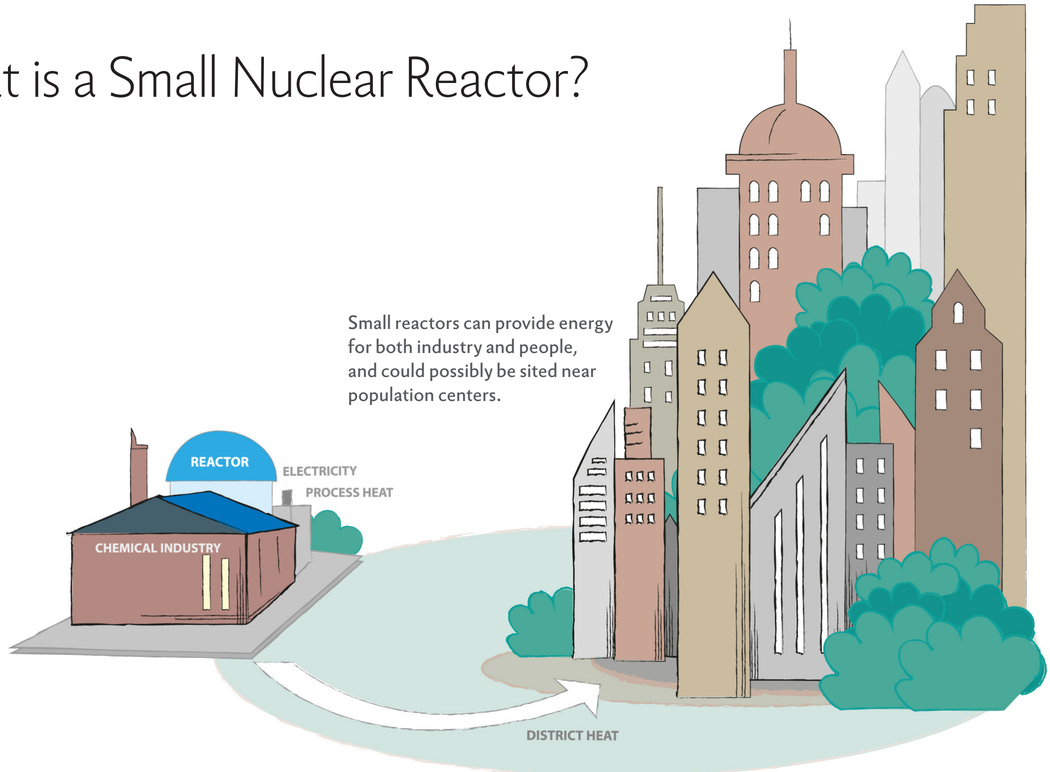
What is a Small Nuclear Reactor?



A small nuclear reactor is roughly 5 to 40 times smaller than a regular large nuclear reactor. They have electrical power output of 50 to 300 megawatts, while large reactors normally have outputs between 1,000 and 1,700 megawatts. Thermal output is two to three times larger. Small reactors are often described with the acronym SMR, which comes from the words Small Modular Reactor.

Small refers to capacity, but otherwise than that, this umbrella-term includes a multitude of different technologies. The most common and technologically mature type is the light water reactor. There are also molten salt reactors, metal cooled reactors, gas cooled reactors, thorium and uranium fuelled reactors and so on. One important property is output temperature, which can be anywhere between roughly 90 and 900 °C and enables different and new applications for nuclear energy.

Many designs will become available within the 2020s and 2030s, which means most countries need to start reforming their regulations and legislation today. In this short brief, you will learn about some of these reactors and the things they can be used for.

MICRO REACTORS

Micro-reactors are even smaller, with capacity less than 50 megawatts. They can be used for isolated communities, remote mining activities, for small island electricity grids and even for military outposts or camps. They replace expensive and hard-to-transport diesel generation.

PASSIVE SAFETY

Passive safety means that the reactor shuts down and cools itself without external help such as electric pumps, if something happens. For example, the reactor might sit in a large pool of water that can cool off the residual heat after shutdown.

Pros

- Smaller capacity makes these reactors well suited for local production of heat. Electricity can be transported for longer distances, but heat must be produced locally. Roughly half of our energy is used as heat, so low carbon, low cost and reliable nuclear heat production can be very useful.
- Small reactors are often designed to be manufactured in a factory assembly line or a shipyard instead of constructed on-site. This can cut costs significantly.
- Small reactors can be designed to be simpler, with passive safety features. This can make siting them more flexible, for example near population centres or industrial parks.
- A smaller size means smaller up-front investment. Financing can be easier to arrange, the project easier to manage and quicker to finish, lowering financing costs. Smaller reactors are easier to add to the grid as needed. This is particularly useful for developing nations with growing needs but underdeveloped power grids and more limited financing opportunities.

Cons

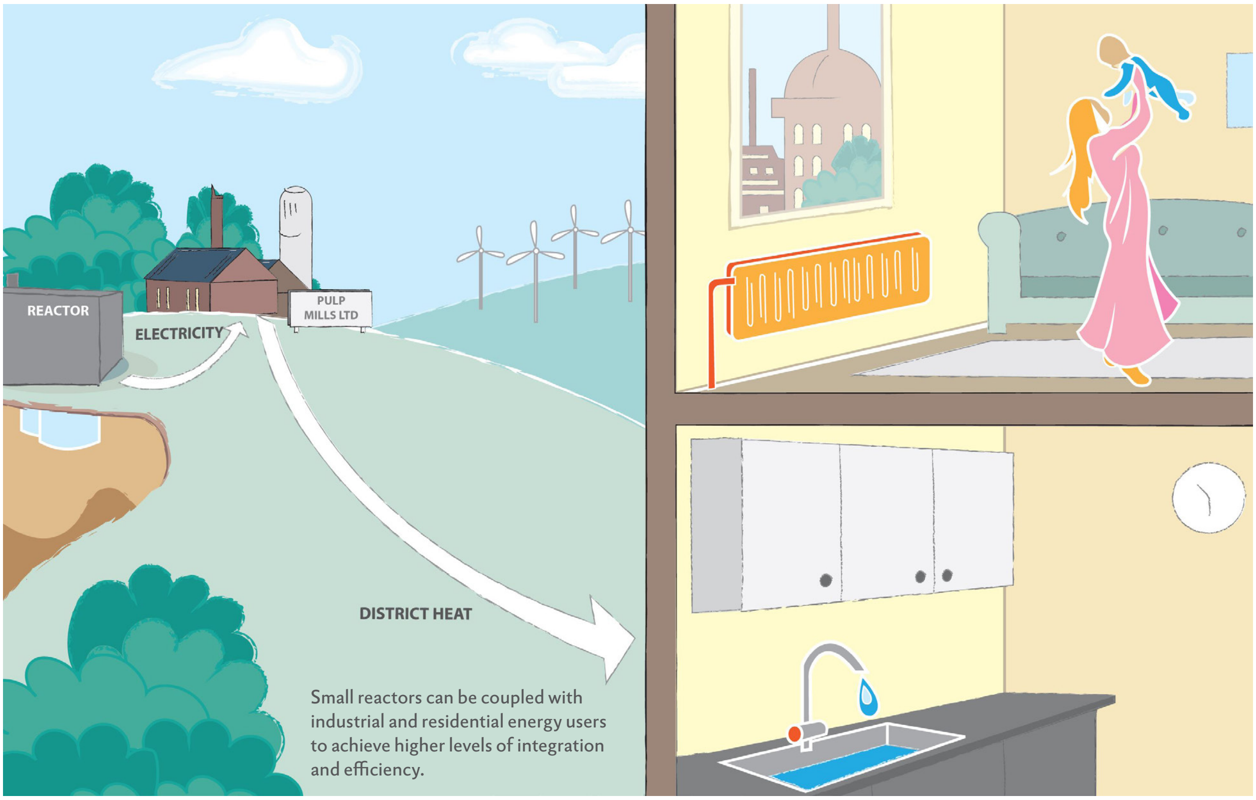
- Smaller reactors don't benefit from the same economics of scale as large reactors do. Yet they often need similar nuclear infrastructure, institutions, regulation, licencing and overall bureaucracy as large reactors.
- We lack suitable legislation and regulations for small reactors and novel uses for nuclear energy. If small reactors are to be manufactured on an assembly line, they would benefit greatly from a single "design licence" applicable globally or over a wider region.
- Some non-light-water reactors use new types of fuel and produce different types of radioactive waste. These might need new regulations, supply chains and management practices.

	Electrical MW	Thermal MW
Micro	0.1-50	0.2-100
Small	50-300	100-900
Medium	300-800	900-2000
Large	800-1700	2000-4500

Approximate electrical and thermal capacities for each size category of nuclear reactors.

KEY CHALLENGES FOR SMALL NUCLEAR

- Public and political awareness and acceptance
- Stakeholder/user awareness and readiness to utilize
- Regulations and market readiness
- Vendor readiness and financing for pre commercial research, development and deployment
- Need for multiple orders to enjoy benefits of series-production.



When can I buy one?

Some First-of-A-Kind small reactors (FOAK) are already being built today, and some have already finished. The Chinese high temperature gas cooled HTR-PM is expected to start operations during 2020, and the pool-type district heating reactor DHR400 should be ready in a couple years' time, by 2021. These are both in China, but even many of the western reactor vendors are planning to have their first reactors finished in the 2020s, which means they will start construction in a couple short years. Russian Rosatom has put two small KLT-40S reactors on a barge that can be towed to suitable location.

The key bottleneck today with small reactors in western countries is not the technology availability, but the lack of proper regulation and legislation for them. This can take many years to prepare, so work needs to start as soon as possible. The current regulations are written for large reactors producing electricity far from population. Some of the key uses for small and advanced reactors is producing heat at smaller scale nearer to population or other industrial activities.

This shift requires new legislation and regulation to happen, and no company will start a project unless there is regulatory certainty.

The Reactors Out There

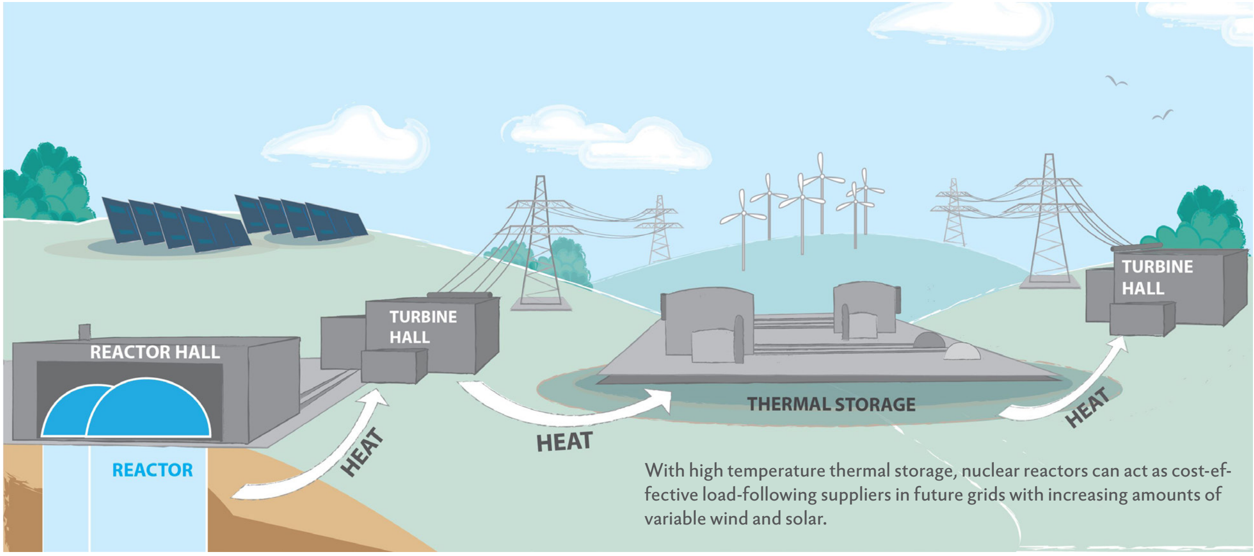
There are dozens of small reactor designs and companies out there, some of the more credible ones are collected on the table below. In addition to these there are many others for example in China, South Korea and the US. Russia is also building multiple designs such as KLT-40S and RITM200, Argentina is finishing up one prototype by 2021. Some reactors are also being designed in the Nordics. Two examples are Swedish LeadCold and their fast lead cooled SEALER-reactor and the Danish Seaborg and their CMSR molten salt reactor.

Name/Company	Reactor Design	Module Power	Coolant/ Moderator	FOAK ETA	Applications
UK SMR/ Rolls Royce	Pressurized water	1276 MWth / 443 MWe	Light water	2030	Electricity and/or heat production
BWRX-300 / GE Hitachi	Boiling water	~900 MWth / 300 MWe	Light water	2030	Electricity and/or heat production
ACP100/CNNC	Integral pressurized water	385 MWth / 125 MWe	Light water	2025	Electricity and/or heat production
NuScale Power Module	Integral pressurized water	200 MWth / 60 MWe	Light water	2026	Electricity and/or heat production
KLT-40S Rosatom	Pressurized water/ on a barge	150 MWth/ 38 MWe	Light water	2019	Electricity and/or heat production
DHR400/CNNC	Pool-type water	400 MWth	Light water	2021	District heating/ cooling
HTR-PM/CNNC	Pebble bed high temp. gas-cooled	250MWth/ 105 MWe	Helium / Graphite	During 2020	Electricity, process heat
IMSR/Terrestrial Energy	Molten salt pool type	400 MWth / 190MWe	Fluoride fuel salt / Graphite	Late 2020s	Electricity and/or heat production

These are just a small sample of the many small reactors under development around the world.

NUWARD – A SMALL FRENCH REACTOR

CHP is In 2019, France also announced their small reactor, Nuward. It is a Pressurized Water Reactor (PWR) with capacity between 300 and 400 MWe, so it is on the larger end of the small reactors, close to Rolls Royce's UK SMR. The basic design should be complete by mid-2020s, with the first demonstration unit being built around 2030.



With high temperature thermal storage, nuclear reactors can act as cost-effective load-following suppliers in future grids with increasing amounts of variable wind and solar.

Small reactors in future grids

The electricity grid of the near future is likely to have much higher shares of wind and solar. This poses challenges and increases the costs of keeping the grid stable, as the production from wind and solar can go up or down very fast. Hydropower is good for providing flexibility, stability and back-up for windless days, as are natural gas turbines, but both have their problems. Hydro can't be scaled up much from current levels, and natural gas is a fossil fuel with emissions.

Many of the small reactors that are being designed aim to provide similar services as natural gas and hydro already do. Their advantage is that nuclear can be scaled up almost without limits and it doesn't produce emissions.

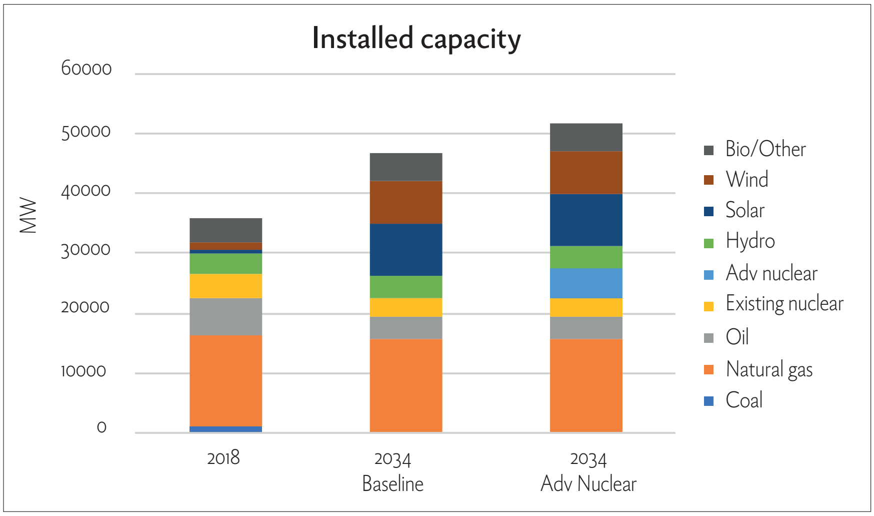
Seen on the picture at the next page is a simulation of a single NuScale Power Module doing flexible production to follow the load of a nearby wind park and demand. The reactor comes with a "turbine bypass" that allows part of the steam to be bypassed from going to the turbine, which lowers the power production. There are many ways to add flexibility to nuclear production, but the key issue is that no operator wants to lose valuable production by ramping it down if there is no incentive to do that.

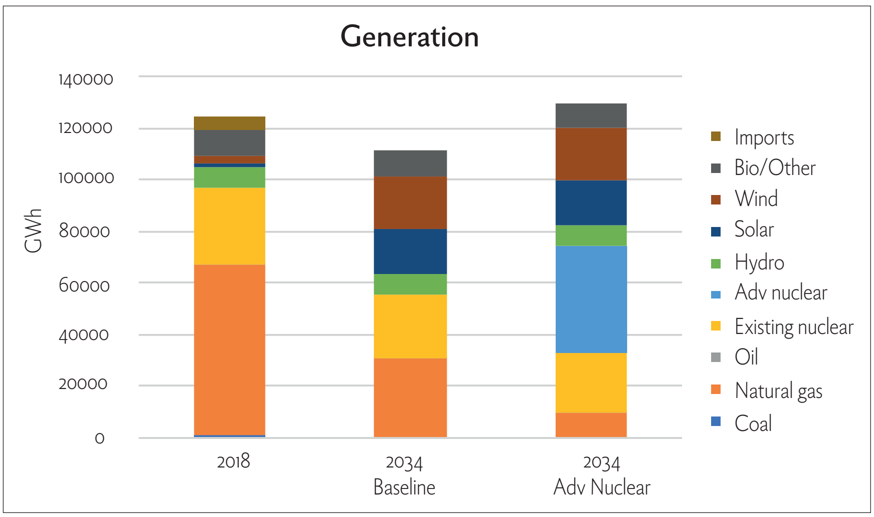
High Temperature Thermal Storage

Nuclear reactors produce hot steam that is turned into electricity in a turbine generator. To add flexibility to the electricity production, a high temperature thermal storage can be used to store the heat from the reactor. Later, this heat can be turned into electricity in a turbine generator. This is potentially a very cost-effective way to add clean, firm and flexible production capacity to the grid.

Some designs, the like molten salt reactors from Terrestrial Energy and Moltex, can use molten salt thermal storage and extra turbines to enable more flexible production. Firebricks is another option, which can be used also with conventional light water reactors. This kind of thermal storage combined with extra turbine-generators can enable the power output to vary for example between 0 and 200 %, while the reactor itself would run at full power all the time.

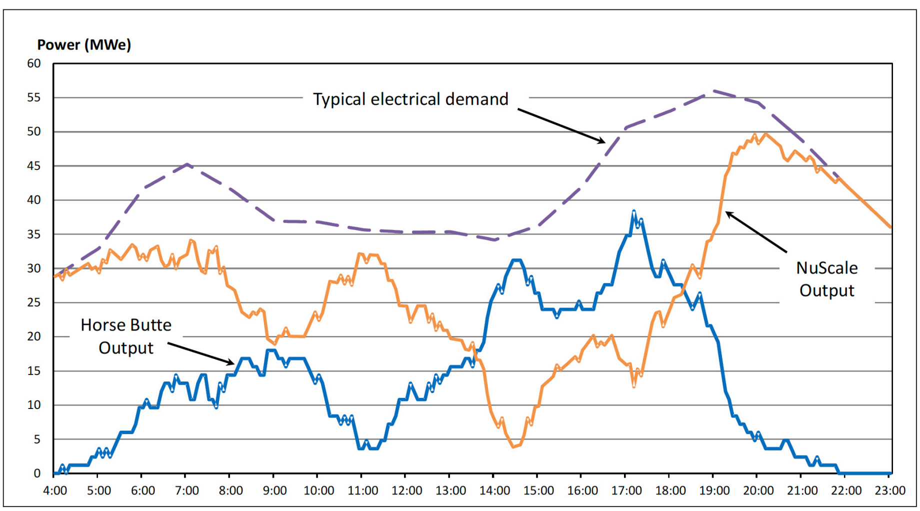
In the graph below, a relatively small amount, 5 GW or about 10 % of total capacity, of this kind of advanced nuclear capacity with thermal storage and extra turbines was added to a renewable-heavy scenario (Installed Capacity -graph). As can be seen on the Generation -graph, the advanced nuclear replaces most of the natural gas production in the modelled system, and a big chunk of the emissions.





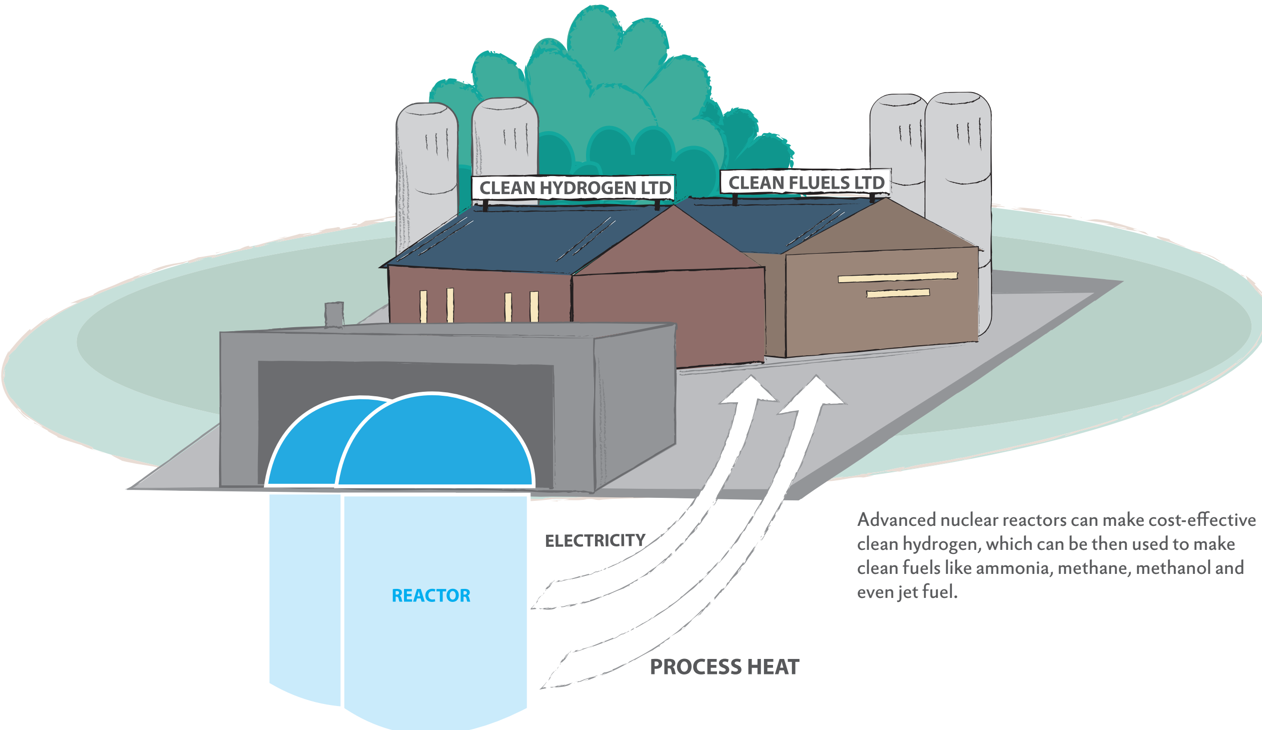
A relatively small amount of advanced nuclear with thermal storage manages to replace most of the natural gas combustion in a future grid with high renewable shares, thus reducing emissions further.

Image has initial modelling of New England with PLEXOS power system software. Based on NREL ReEDS Low Natural Gas Price and Low Renewable Energy Costs scenario. Image Credit: LucidCatalyst Ltd.



NuScale Power Module load following local demand and wind production by using turbine bypass.

D. T. Ingersoll, C. Colbert, Z. Houghton, R. Snuggerud, J. W. Gaston and M. Empey, "Can Nuclear Energy and Renewables be Friends?" Proceedings of the 2015 International Congress on Advances in Nuclear Power Plants (ICAPP 2014)
Initial modelling of New England with PLEXOS power system software. Based on NREL ReEDS Low Natural Gas Price and Low Renewable Energy Costs scenario. Image Credit: LucidCatalyst Ltd.



Advanced nuclear reactors can make cost-effective clean hydrogen, which can be then used to make clean fuels like ammonia, methane, methanol and even jet fuel.

Nuclear Beyond electricity

Nuclear reactors have traditionally been used for making electricity, but many of the new, smaller reactors can be used for other things as well. While electricity accounts for a fifth of our global energy use, roughly half our energy is used as heat, and around a quarter is used in transportation.

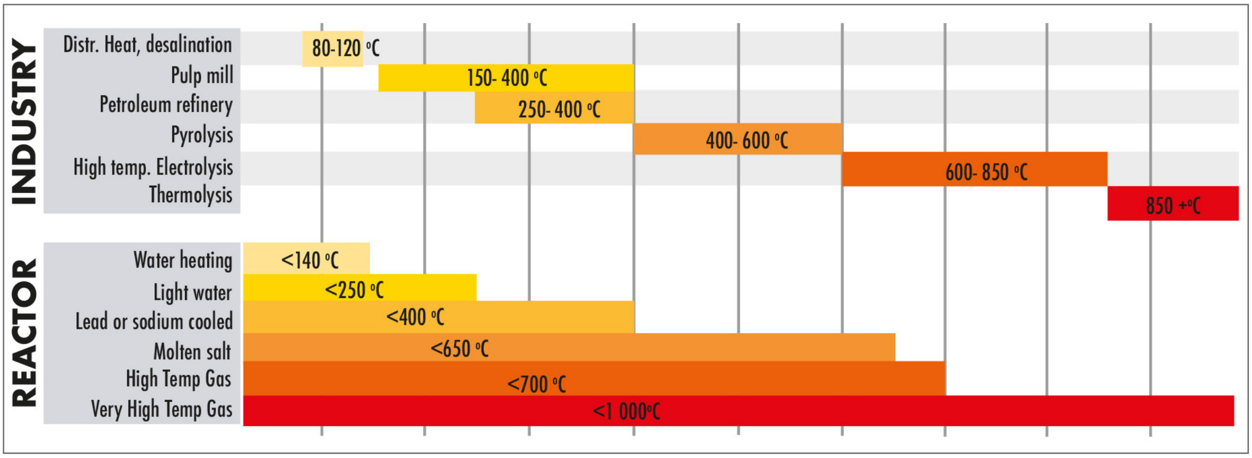
According to MacKinsey (2018), industry causes around 28 %, or 15 gigatons, of our CO_2 emissions. Around two thirds (~10 gigatons) of that comes from direct industrial processes and one third (~5 gigatons) comes from electricity used by industry. Industries such as refineries, chemical plants, pulp and paper mills, manufacturing, metal and cement production and many others use high grades of heat. Locally this use is relatively small scale and could be particularly well suited for small nuclear reactors.

Low grade heat for space heating/cooling, desalination

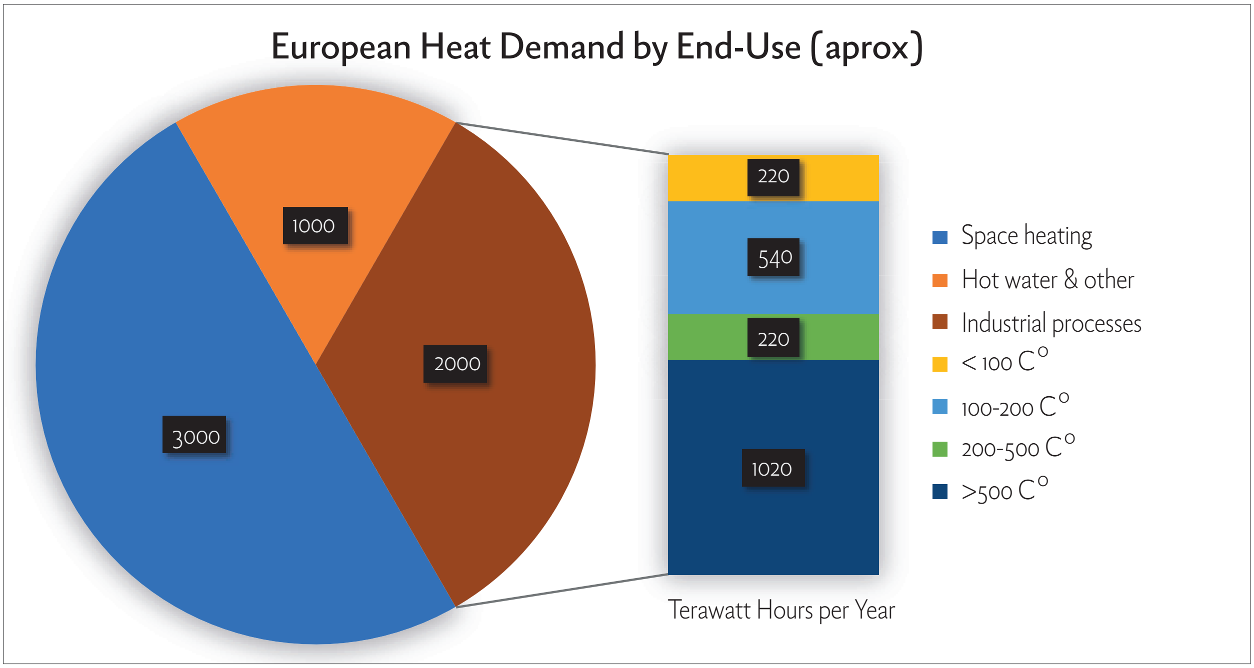
Around two thirds of heat is used at relatively low temperatures of around 80 to 120 °C. This includes space heating and hot water use and some industrial uses. These temperatures can also be used for water desalination and district cooling.

Such temperatures can be made reliably and cost-effectively through many means, including waste heat streams with heat pumps, combined heat and power (CHP) in power plants and heat-only nuclear reactors.

A small nuclear reactor that makes low-grade heat can be a very simple design. For example, such reactor could sit at the bottom of a “swimming pool” and just heat the water that is then used for district heating, desalination or something else. Because no electricity is produced, it doesn’t need pressure vessels, steam generators or turbines.



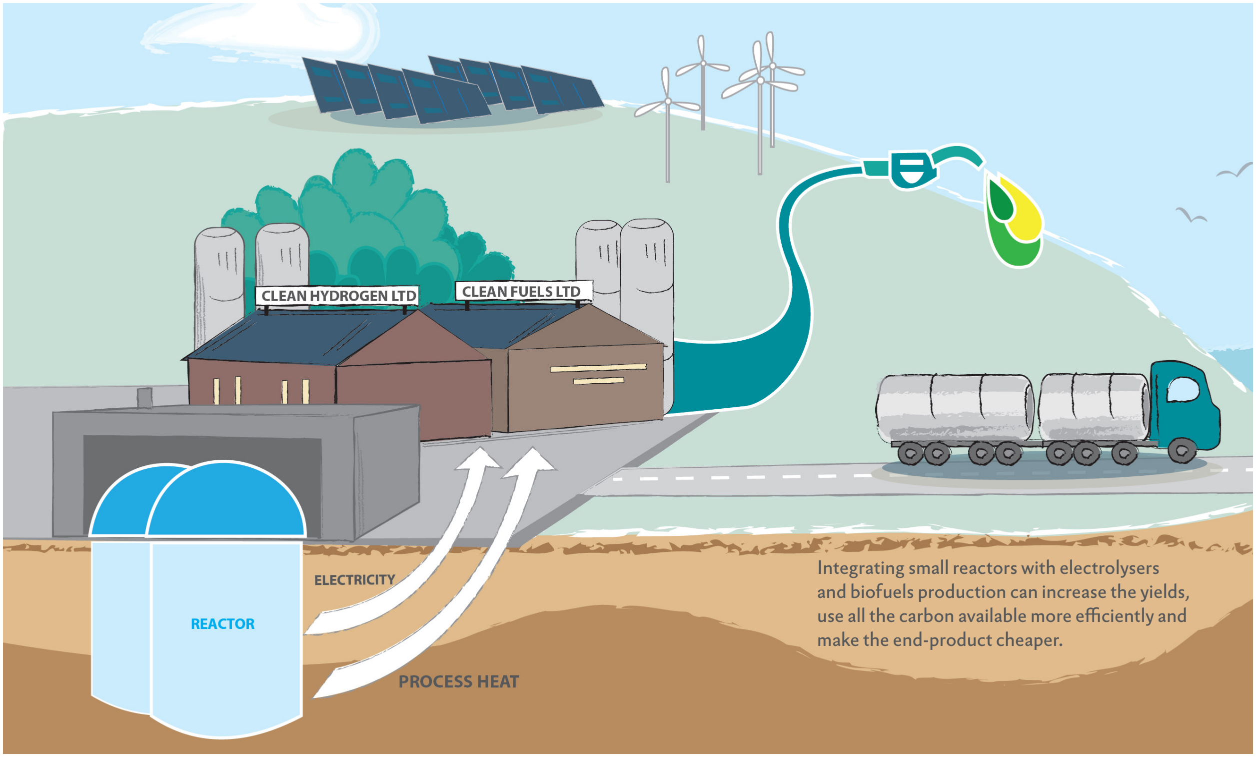
Temperature ranges used in various industries compared with temperature ranges produced by different types of reactors.



Roughly half of energy is used as heat. In Europe, the total heat use is roughly 6,000 TWh/year. It is split for different use-cases and temperatures as seen on the graph.

COMBINED HEAT AND POWER – CHP

CHP is an effective way to produce both electricity and low-grade heat for various purposes such as district heating or desalination. In CHP, one gives up some of the electricity production efficiency but gets more useful heat in return. Depending on how it is done, the overall efficiency of the CHP power plant is usually between 70 to 90 %, more than double what is achieved with electricity-only production.



Forestry, Pulp and Advanced Bioproducts

Biorefineries, such as pulp mills, use a lot of energy and are large single-point sources of emissions. They require heat between 150 and 400 °C and often utilize hydrogen as well, especially if they make advanced biofuels as well. The energy is today produced mainly by combusting the waste and by-products such as bark, branches and black liquor (see box).

Using small nuclear reactors as the energy source could save some of the biomass for other uses, such as feedstock for advanced biofuels or chemicals. With a source of affordable and clean hydrogen (more info on nuclear hydrogen later), the yields for liquid biofuels could also be significantly increased, and their relative emissions reduced.

PYROLYSIS AND BIOCHAR – NEGATIVE EMISSIONS BIOFUELS

Pyrolysis can be used to make carbon-negative products and fuels from a feedstock such as biomass. One product is biochar which can be used to improve farming soil while also storing carbon in the soil for centuries. It also produces pyrolysis oil and syngas. Often these two are burned to produce the heat (between 400 and 600 °C) for the pyrolysis process, but producing that heat with nuclear energy instead, these products could be used to make valuable liquid fuels and chemicals.

Making and using hydrogen

Petroleum refining

Petroleum refineries are among the largest single-point sources of emissions, often emitting millions of tons of CO_2-equivalent per year. They use heat at 250 to 400 °C to distil different products from crude oil. They also use hydrogen to increase the share of valuable products – such as gasoline – they can derive from crude oil. Hydrogen is used to hydrocrack longer hydrocarbons into shorter ones and for desulphurization of the crude oil.
Both the heat and the hydrogen are today made with fossil fuels, but they can also be made with small nuclear reactors on-site. Either a light water reactor with topping heat (see box) or a higher temperature reactor.

Making and Using Hydrogen

Affordable and clean hydrogen will be key to deep decarbonization of many sectors. It is widely used as a feedstock in the chemical and petrochemical industry. It is the main ingredient of ammonia, a key component of nitrogen fertilizer that is essential for modern agriculture. In the future, it could be used in steel production to replace coke in the reduction of iron (see box).

Hydrogen can also be used directly as a fuel or made into synthetic methane, methanol and even gasoline, diesel and jet fuel – and many other important chemicals. Around 95 % of our hydrogen is currently derived from fossil fuels, namely natural gas, oil and coal. This causes significant emissions.

Making Clean Hydrogen

There are several ways to make clean hydrogen. Electrolysis makes hydrogen from water with electricity at roughly 50-70 % efficiency. High temperature steam electrolysis, HTSE, can convert over 90 % of used electricity into hydrogen, but it needs a source of high temperature steam as well (600-800 °C). The steam and electricity can be supplied with a high temperature reactor such as a gas-cooled or a molten-salt reactor. Thermolysis, at 800+ °C, can be used to make hydrogen without electricity, just with heat. Such high temperature requires either topping heat or a gas-cooled very high temperature reactor. Both HTSE and nuclear thermolysis are still under R&D, with estimated commercial availability in the 2020s or later. Target costs are below 2 € /kg of hydrogen, which is comparable to current costs in Europe.

TOPPING UP THE HEAT

If a process uses 400 °C steam and a reactor provides only 300 °C steam, this is not an insurmountable problem. Most of the energy goes into making the steam (boiling water), not increasing its temperature. The steam temperature can be topped up using electricity, natural/biogas, hydrogen or something else while still achieving significantly lower emissions.

BLACK LIQUOR FOR LIQUID FUELS

Black liquor is a by-product from forest industry. It is also a good starting point for making biofuels for transportation. It's currently combusted to produce heat and electricity for the pulp mill's processes and to retrieve the catalytic materials used in the process. If we can develop a cost-effective way to retrieve these materials, we could use the black liquor as a feedstock to make for example jet fuel.

LOW-CARBON STEEL

Steel maker SSAB plans to move its steel production from coke (pure carbon) to hydrogen to reduce emissions. With traditional electrolysis – making hydrogen from water with electricity – the company has estimated that it would need roughly 25 terawatt hours of electricity per year just for producing the hydrogen. This is roughly what is produced by two large EPR reactors such as Olkiluoto 3 and Flamanville.

This folder was produced by Think Atom, a non-profit think tank that explores and communicates the ways that we could use nuclear energy to decarbonize our society faster and more cost-effectively. Thinkatom.net / info@thinkatom.netemissions.

THINK ATOM

SMALL NUCLEAR REACTORS AND WHERE TO USE THEM

This folder gives you the quick essentials on what are small nuclear reactors and their pros and cons, when are they coming to the market, and most importantly, what they can be used for; not just electricity, but valuable services to the power grid, district heating of cities, desalination of seawater, many industrial processes and even manufacturing of cost-effective clean hydrogen.

For more information on small nuclear reactors, visit for example the regularly updated World Nuclear Association's webpage on the subject: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx or http://tinyurl.com/y5fc2olm

Energiforsk is the Swedish Energy Research Centre – an industrially owned body dedicated to meeting the common energy challenges faced by industries, authorities and society. Our vision is to be hub of Swedish energy research and our mission is to make the world of energy

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