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Cooling power plants

(Updated July 2013)

- **The amount of cooling required by any steam-cycle power plant (of a given size) is determined by its thermal efficiency. It has essentially nothing to do with whether it is fuelled by coal, gas or uranium.**
- **However, currently operating nuclear plants often do have slightly lower thermal efficiency than coal counterparts of similar age, and coal plants discharge some waste heat with combustion gases, whereas nuclear plants rely on water.**
- **Nuclear power plants have greater flexibility in location than coal-fired plants due to fuel logistics, giving them more potential for their siting to be determined by cooling considerations.**

The most common types of nuclear power plants use water for cooling in two ways:

- To convey heat from the reactor core to the steam turbines.
- To remove and dump surplus heat from this steam circuit. (In any steam/ Rankine cycle plant such as present-day coal and nuclear plants there is a loss of about two-thirds of the energy due to the intrinsic limitations of turning heat into mechanical energy.)

The bigger the temperature difference between the internal heat source and the external environment whe the surplus heat is dumped, the more efficient is the process in achieving mechanical work – in this case, turning a generator[1]. Hence the desirability of having a high temperature internally and a low temperature in the external environment. This consideration gives rise to desirably siting power plants alongside very cold water.*

* Many power plants, fossil and nuclear, have higher net output in winter than summer due to differences in cooling water temperature.

1. Steam cycle heat transfer

For the purpose of heat transfer from the core, the water is circulated continuously in a closed loop steam cycle and hardly any is lost. It is turned to steam by the primary heat source in order to drive the turbine to do work making electricity[2], and it is then condensed and retuned under pressure to the heat source in a closed system.[3] A very small amount of make-up water is required in any such system. The water needs to be clean and fairly pure.[4]

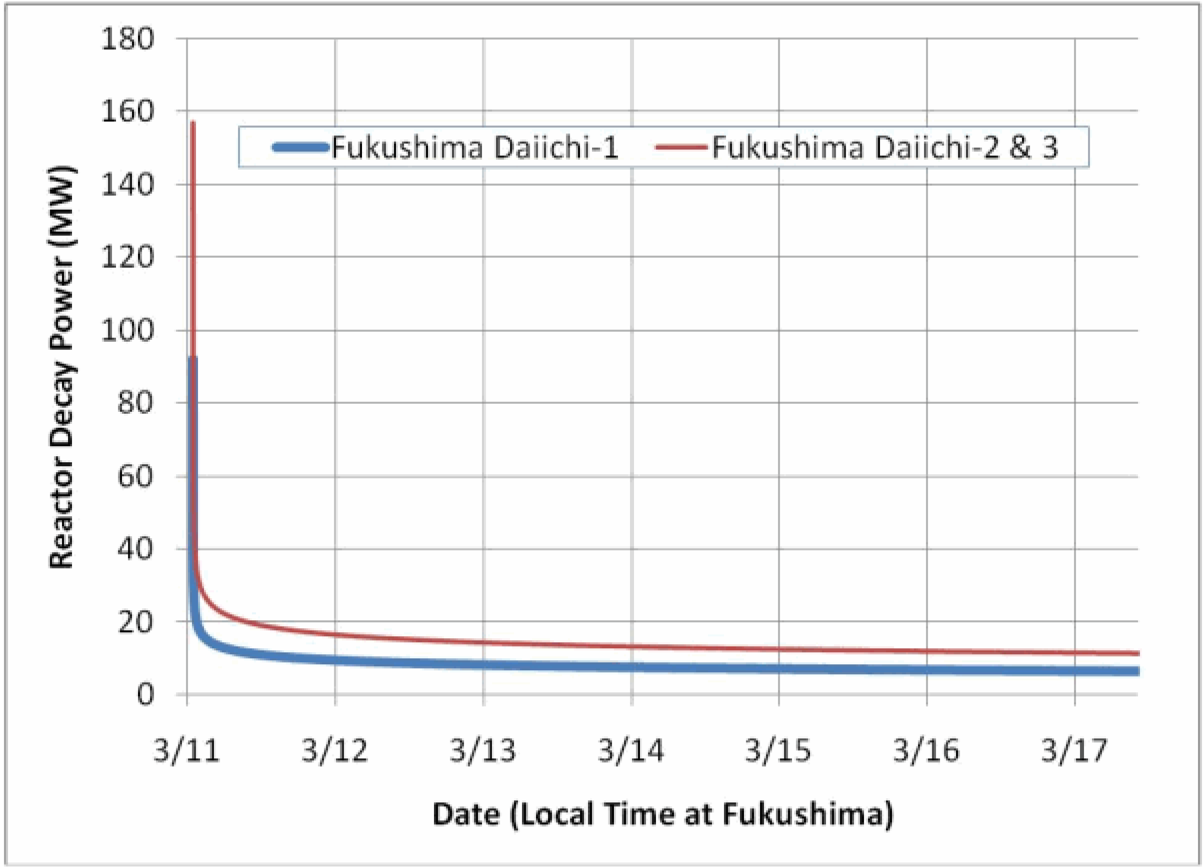
This function is much the same whether the power plant is nuclear, coal-fired, or conventionally gas-fired. Any steam cycle power plant functions in this way. At least 90% of the non-hydro electricity in every countr is produced thus.

In a nuclear plant there is an additional requirement. When a fossil fuel plant is shut down, the source of heat is removed. When a nuclear plant is shut down some heat continues to be generated from radioactive decay, though the fission has ceased. This needs to be removed reliably, and the plant is designed to enable and assure this, both with routine cooling and also Emergency Core Cooling Systems (ECCS) provided in case of major problem with primary cooling. The routine cooling is initially with the main steam supply circuit bypassing the turbine and dumping heat into the condenser. After pressure drops, a residual heat removal system is relied upon with its own heat exchanger. The intensity of this decay heat diminishe with time, rapidly at first, and after a day or two ceases to be a problem if circulation is maintained.*

* When Kashiwazaki-Kariwa 7 nuclear reactor automatically shut down because of a severe earthquake in 2007, it took 16 hours for the coolant temperature to diminish from 287 to 100ºC so t

it would no longer boil. "Cold shutdown" is when the primary circuit is at atmospheric pressure and not boiling.

Decay heat in fuel at Fukushima Daiichi reactors



2. Cooling to condense the steam and discharge surplus heat

The second function for water in such a power plant is to cool the system so as to condense the low-pressure steam and recycle it. As the steam in the internal circuit condenses back to water, the surplus (waste) heat which is removed from it needs to be discharged by transfer to the air or to a body of water.

This is a major consideration in siting power plants, and in the UK siting study in 2009 for nuclear plants al recommendations were for sites within 2 km of abundant water – sea or estuary.

This cooling function to condense the steam may be done in one of three ways:

- **Direct or "once-through"** cooling. If the power plant is next to the sea, a big river, or large inland water body it may be done simply by running a large amount of water through the condensers in a single pass and discharging it back into the sea, lake or river a few degrees warmer and without much loss from the amount withdrawn[5]. That is the simplest method. The water may be salt or fresh. Some small amount of evaporation will occur off site due to the water being a few degrees warmer.
- **Recirculating or indirect cooling.** If the power plant does not have access to abundant water, cooling may be done by passing the steam through the condenser and then using a cooling tower, where an updraught of air through water droplets cools the water. Sometimes an on-site pond or canal may be sufficient for cooling the water. Normally the cooling is chiefly through evaporation, with simple heat transfer to the air being of less significance. The cooling tower evaporates up to 5% of the flow and the cooled water is then returned to the power plant's condenser. The 3 to 5% or so is effectively consumed, and must be continually replaced. This is the main type of recirculating or indirect cooling.
- **Dry cooling.** A few power plants are cooled simply by air, without relying on the physics of evaporation. This may involve cooling towers with a closed circuit, or high forced draft air flow through a finned assembly like a car radiator.

With a fossil-fuel power plant some of the heat discharged is in the flue gases. With a large coal-fired plant some 15% of the waste heat is through the stack, whereas in a nuclear power plant virtually all the waste heat has to be dumped into the condenser cooling water. This gives rise to some difference in water consumption or use between a nuclear and a coal plant. (A gas turbine plant will discharge most of its was heat in the exhaust.)

Beyond this, and apart from size, any differences between plants is due to **thermal efficiency**, ie how muc heat has to be discharged into the environment, which in turn largely depends on the operating temperatu in the steam generators. In a coal-fired or conventionally gas-fired plant it is possible to run the internal boilers at higher temperatures than those with finely-engineered nuclear fuel assemblies which must avoid damage. This means that the efficiency of modern coal-fired plants is typically higher than that of nuclear plants, though this intrinsic advantage may be offset by emission controls such as flue gas desulfurisation (FGD) and in the future, carbon capture and storage (CCS).

A nuclear or coal plant running at 33% thermal efficiency will need to dump about 14% more heat than one at 36% efficiency.[6] Nuclear plants currently being built have about 34-36% thermal efficiency, depending on site (especially water temperature). Older ones are often only 32-33% efficient. The relatively new Stanwell coal-fired plant in Queensland runs at 36%, but some new coal-fired plants approach 40% and o of the new nuclear reactors claims 39%.

Table 1. Some thermal efficiencies of different coal-fired technologies

Country	Technology	Thermal Efficiency	Projected efficiency with CCS
Australia	Black ultra-supercritical WC	43%	33%
	Black supercritical AC	39%	
	own ultra-supercritical WC	35%	27%
	Brown supercritical WC	33%	
	Victorian brown 2009 WC	25.6%	
Belgium	Black supercritical	45%	
China	Black supercritical	46%	
Czech Republic	Brown PCC	43%	38%
	Brown IGCG	45%	43%
Germany	Black PCC	46%	38%

	Brown PCC	45%	37%
Russia	Black ultra-supercritical PCC	47%	37%
USA	Black PCC & IGCC	39%	39%

OECD Projected Costs of Generating Electricity 2010, Tables 3.3; Victorian brown coal from ESAA 2010 report.

PCC= pulverised coal combustion, AC= air-cooled, WC= water-cooled

(No nuclear efficiency data in this report, but comparable Generation III efficiency is often quoted as about 36%, and see Table 2.)

Table 2: Selected examples of the operating nuclear power reactors

	Reactor	**Capacity (MWe net)**	**Type/ cooling method**	**start-up**	**thermal efficiency**
Canada	Darlington 1	881	PHWR/ lake, once-through	1977	31.2%
France	Chooz B1	1455	PWR/ tower, natural draft	1983	29.5%
USA	Peach Bottom 2	1055	BWR/ river, once through (tower, forced draft on standby)	1973	32.3%
Japan	Ohi 4	1127	PWR/ sea, once-through	1992	34.3%
South Korea	Hanbit/ Yonggwang 6	996	PWR/ sea, once-through	2002	37.4%
Russia	Beloyarsk 3	560	FBR/ lake, once-through	1980	41.5%

Nuclear Engineering handbook 2010 data. Net capacity (MWe) is net of losses from the actual energy usage of the plant. BWR = boiling water reactor, PWR= pressurised water reactor, PHWI

pressurised heavy water reactor (CANDU). FBR= fast breeder reactor (at higher temperature).

In Europe (especially Scandinavia) low water temperature is an important criterion for power plant location For a planned Turkish nuclear plant, there is a one percent gain in output if any particular plant is sited on the Black Sea coast with cooler water (average 5°C lower) than on the Mediterranean coast. For the new UAE nuclear power plants, because the Gulf seawater at Braka is about 35°C, instead of about 27°C as with the Shin Kori 3 & 4 reference units, larger heat exchangers and condensers will be required.

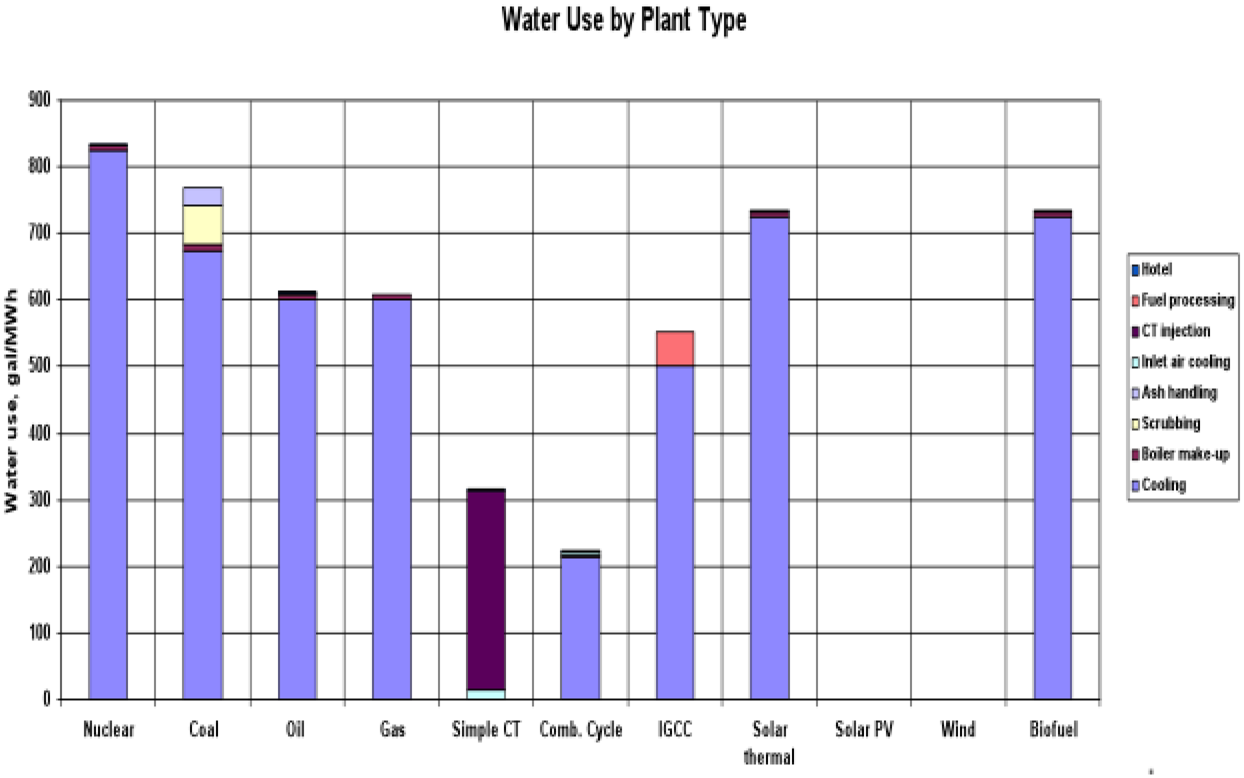
According to a 2006 Department of Energy (DOE) report discussed in the Appendix, in the USA 43% of thermal electric generating capacity uses once-through cooling, 42% wet recirculating cooling, 14% coolin ponds and 1% dry cooling (this being gas combined cycle only). The spreads for coal and for nuclear are similar. For 104 US nuclear plants: 60 use once-through cooling, 35 use wet cooling towers, and 9 use du systems, switching according to environmental conditions. This distribution is probably similar for continen Europe and Russia, though UK nuclear power plants use only once-through cooling by seawater, as do all Swedish, Finnish, Canadian (Great Lakes water), South African, Japanese, Korean and Chinese plants. IAEA figures show 45% of nuclear plants use the sea for once-through cooling, 15% use lakes, 14% rivers and 26% use cooling towers.

Gas combined cycle (combined cycle gas turbine – CCGT) plants need only about one third as much engineered cooling as normal thermal plants (much heat being released in the turbine exhaust), and these often use dry cooling for the second stage.*

* CCGT plants have an oil or gas-fired gas turbine (jet engine) coupled to a generator. The exhaust is passed through a steam generator and the steam is used to drive another turbine. This results in ove thermal efficiency of over 50%. The steam in the second phase must be condensed either with an air cooled condenser or some kind of wet cooling.

Combined heat and power (CHP) plants obviously need less engineered cooling provision that others sinc the by-product heat is actually used for something and not dissipated uselessly.

Due to the heat loss through combustion gases in the stack, simple-cycle coal plants have a lower heat rejection load through the condenser and cooling system than simple-cycle nuclear plants. However, they also have water needs for scrubbing and coal ash handling, which diminishes the difference between wate needs for nuclear and coal-fired plants. The basic difference, estimated by the US Electric Power Researc Institute (EPRI) as typically 15-25%, is not significant enough to be a factor in making a selection between nuclear and coal. EPRI considers that in general, available water savings from approaches such as air cooling, non-traditional water sources, recycling plant waste water streams and increasing thermal energy conversion efficiency far outweigh any differences between nuclear and coal water requirements.



EPRI 2010 (some 15% of coal plant waste heat is discharged through the stack, rather than cooling water
NB US gal =3.79 litres

Direct or Once-through wet cooling

If a coal or nuclear plant is next to a large volume of water (big river, lake or sea), cooling can be achieved by simply running water through the plant and discharging it at a slightly higher temperature. There is then hardly any use in the sense of consumption or depletion on site, though some evaporation will occur as it cools downstream. The amount of water required will be greater than with the recirculating set-up, but the water is withdrawn and returned, not consumed by evaporation. In the UK the water withrawal requirement for a 1600 MWe nuclear unit is about 90 cubic metres per second (7.8 GL/d).

Many nuclear power plants have once-through cooling, since their location is not at all determined by the source of the fuel, and depends first on where the power is needed and secondly on water availability for cooling. Using seawater means that higher-grade materials must be used to prevent corrosion, but cooling is often more efficient. In a 2008 French government study, siting an EPR on a river instead of the coast would decrease its output by 0.9% and increase the kWh cost by 3%.

Any nuclear or coal-fired plant that is normally cooled by drawing water from a river or lake will have limits imposed on the temperature of the returned water (typically 30°C) and/or on the temperature differential between inlet and discharge. In hot summer conditions even the inlet water from a river may approach the limit set for discharge, and this will mean that the plant is unable to run at full power. In mid 2010 TVA had to reduce power at its three Browns Ferry units in Alabama to 50% in order to keep river water temperature below 32°C, at a cost of some $50 million to customers. This was the same week when Rhine and Neckar River temperatures in Baden-Wuerttemberg approached the critical 28°C, and nuclear and coal-fired plant were threatened with closure. In August 2012 one unit of Millstone power station in Connecticut was closed because the seawater in Long Island Sound exceeded 24°C.

Sometimes a supplementary cooling tower is used to help, giving a dual system, as with TVA's Browns Ferry and Sequoyah plants in USA, many inland plants in France and Germany, and at the Huntly plant in

New Zealand, but this means that some water is then lost by evaporation. In the mid 2010 Brown's Ferry situation mentioned above, the six "seasonal" mechanical -draft cooling towers 18-24 m high were operati at full capacity and had been for most of the summer. TVA will spend $160 million to add one larger (c 50 m) mechanical-draft cooling tower there by mid 2011 and then progressively replace four existing ones wit improved designs by 2013.

Recirculating or indirect wet cooling

Where a power plant does not have abundant water, it can discharge surplus heat to the air using recirculating water systems which mostly use the physics of evaporation.

Cooling towers with recirculating water are a common visual feature of power plants, often seen with condensed water vapour plumes. Sometimes in a cool climate it is possible to use simply a pond, from which hot water evaporates.

Most nuclear power (and other thermal) plants with recirculating cooling are cooled by water in a condens circuit with the hot water then going to a cooling tower. This may employ either natural draft (chimney effe or mechanical draft using large fans (enabling a much lower profile but using power*). The cooling in the tower is by transferring the water's heat to the air, both directly and through evaporation of some of the water. In the UK the water requirement for a 1600 MWe nuclear unit is about 2 cubic metres per second (173 ML/d), this being about half for evaporation and half for blow-down (see below).

* Chinon B in France (4x905 MWe) and the proposed Calvert Cliffs plant in the USA (1650 MWe) use low-profile forced-draft cooling towers. At Chinon B one cooling tower per unit is 30 m hi (instead of 155 m required for a natural draft type there), 155 m diameter, and uses 8 MWe for its 18 fans (0.9% of power). At Calvert Cliffs the cooling tower fans will use about 20 MWe (1.2% power.

Chinon B, France, with low-profile forced-draft cooling towers

Credit: EDF/Marc Mourceau

The most common configuration for natural draft towers is called counterflow. These towers have a large concrete shell with a heat exchange 'fill' in a layer above the cold air inlet at the base of the shell. The air warmed by the hot water rises up through the shell by convection (the chimney effect), creating a natural draft to provide airflow to cool the hot water which is sprayed in at the top. Other configurations include crossflow, where the air moves laterally through the water, and co-current, where the air moves in the sam direction as the water droplets. These towers do not require fans and have low operating but significant maintenance costs. For a large plant they may need to be over 200 metres high. They are used in large nuclear and coal-fired plants in Europe, eastern USA, Australia, and South Africa

Mechanical draft cooling towers have large axial flow fans in a timber and plastic structure. The fans provic the airflow and are able to provide lower water temperatures than natural draft towers, particularly on hot d days. However, they have the disadvantage of requiring auxiliary power, typically about 1% of the plant's output, and up to 1.2% of it. Mechanical draft towers are used exclusively in central and western USA sinc they can provide a more controlled performance over a wide range of conditions, ranging from freezing to hot and dry. Also they are less visually obtrusive, being less than 50 m high.

Such cooling towers give rise to water consumption, with up to 3.0 litres being evaporated for each kilowat hour produced[7], depending on conditions[8]. This evaporative water loss by phase change of a few percent of it from liquid to vapour is responsible for removing most of the heat from the coolant water at the cost of only a small fraction of the volume of the circulating liquid (though a rather large fraction of the wate actually withdrawn from lake or stream).

Cooling towers with recirculating water reduce the overall efficiency of a power plant by 2-5% compared with once-through use of water from sea, lake or large stream, the amount depending on local conditions. 2009 US DOE study says they are about 40% more expensive than a direct, once-through cooling system

Water evaporating from the cooling tower leads to an increasing concentration of impurities in the remainir coolant. Some bleed – known as "blowdown" – is needed to maintain water quality, especially if the water recycled municipal wastewater to start with - as Palo Verde, Arizona*, and proposed for Jordan's Majdal plant. Replacement water required is thus about 50% more than actual evaporation replacement, so this kind of system consumes (by evaporation) up to 70% of the water withdrawn.

* Some 220 ML/day of treated sewage is pumped 70 km from Phoenix, Az to the 3-unit 3875 MWe plant. Evaporation is 76 ML/day per unit, and blowdown 4.7 ML/day at a salinity approx tha seawater, discharged to evaporation ponds, hence about 2.6 L/kWh is used. It has three mechanical-draft cooling towers for each unit.

Even with the relatively low net water requirement for recirculating cooling, large power plants can exceed what is readily available from a river in summer. The 3000 MWe Civaux nuclear plant in France has 20 GL of water stored in dams upstream to ensure adequate supply through drought conditions.

A few nuclear plants employ cooling ponds, which are another type of closed-cycle cooling that reduce the evaporative losses associated with cooling towers. Cooling ponds require a significant amount of land, anc may not be feasible for other reasons. A cooling pond has the advantage of transferring a larger percentag of waste heat to the atmosphere via convection or slower evaporation due to lower differential temperature reducing the rate of evaporation and thus the rate of consumptive water loss relative to cooling towers. Als their environmental impacts are typically less than direct cooling.

Despite many coal and nuclear plants using wet cooling towers, in the USA electric power generation accounts for only about 3% of all freshwater consumption, according to the US Geological Survey - some 15.2 gigalitres per day (5550 GL/yr). This would be simply for inland coal and nuclear plants without acces to abundant water for once-through cooling. Australian coal-fired power plants consume about 400 GL/yr[9 – the equivalent of Melbourne's water supply.

Dry cooling

Where access to water is even more restricted, or environmental and aesthetic considerations are prioritised, dry cooling techniques may be chosen. As the name suggests, this relies on air as the medium of heat transfer, rather than evaporation from the cooling circuit. Dry cooling means that minimal water los is achieved. There are two basic types of dry cooling techniques available.

One design works like an automobile radiator and employs high-flow forced draft past a system of finned tubes in the condenser through which the steam passes, simply transferring its heat to the ambient air directly. The whole power plant then uses less than 10% of the water required for a wet-cooled plant,[10] but a lot of power (around one to 1.5 percent of power station's output) is consumed by the large fans required.[11] This is direct dry cooling, using air-cooled condenser (ACC) and it is not currently in use on any nuclear power plant.

Alternatively there may still be a condenser cooling circuit as with wet recirculating cooling, but the water i
it is enclosed and cooled by a flow of air past finned tubes in a cooling tower.* Heat is transferred to the ai
but inefficiently. This technology is not favoured if wet cooling depending on evaporation is possible, but energy use is only 0.5% of output. This appears to be the back-up system planned for Loviisa in Finland i
2014.

* Some mechanical draft towers are a hybrid design incorporating a dry section above the wet section. The mode of cooling used depends on the season, with dry cooling being preferred duri
the colder months.

In both cases there is no dependence on vaporization and hence no evaporative loss of cooling water. Th
use of fans also allows for greater control over cooling than relying simply on natural draught. However th
heat transfer is much less efficient and hence requires much larger cooling plant which is mechanically more complex. Eskom in South Africa quotes dry-cooled plants as having total station water consumption under 0.8 lites/kWh, this being for steam cycle losses (cf about 2.5 L/kWh for wet-cooled plants). Eskom is building two of the largest coal-fired plants in the world – each 6 x 800 MWe – and one of these will be the largest dry-cooled plant in the world.

Hardly any US generating capacity uses dry cooling, and in the UK it has been ruled out as impractical an
unreliable (in hot weather) for new nuclear plants. A 2009 US DOE study says they are three to four times more expensive than a recirculating wet cooling system. All US new plant licence applications have rejecte

dry cooling as infeasible for the site or unacceptable because of lost electrical generating efficiency and significantly higher capital and operating costs. For large units there are also safety implications relating to removal of decay heat after an emergency shutdown with loss of power. It is unlikely that large nuclear plants will adopt dry cooling in the foreseeable future.

However, two of the US small modular reactor (SMR) designs – Holtec SMR-160 and B&W mPower – use dry cooling or can do so. B&W claims 31% thermal efficiency using an air-cooled condenser.

Both types of dry cooling involve greater cost for the cooling set-up and are much less efficient than wet cooling towers using the physics of evaporation[12] since the only cooling is by relatively inefficient heat transfer from steam or water to air via metal fins, not by evaporation. In a hot climate the ambient air temperature may be 40 degrees C, which severely limits the cooling potential compared with a wet bulb temperature of maybe 20ºC which defines the potential for a wet system. However, if dry systems are retrofitted, the wet system is still available for hot weather.

Australian projected figures for coal* show a 32% drop in thermal efficiency for air cooling versus water, eg from 33% to 31%.

* In OECD *Projected Costs of Generating Electricity* 2010, Tables 3.3.

Environmental and social aspects of cooling

Each of the different methods of cooling entails their own set of local environmental and social impacts and is subject to regulation.

In the case of direct cooling, impacts include the amount of water withdrawn and the effects upon organism in the aquatic environment, particularly fish and crustaceans. This latter includes both kills due to impingement (trapping of larger fish on screens) and entrainment (drawing of smaller fish, eggs and larvae through cooling systems) and the change in ecosystem conditions brought about by the increase in temperature of the discharge water.

In the case of wet cooling towers, impacts include water consumption (as distinct from just abstraction) an the effects of the visual plume of vapour emitted from the cooling tower. Many people consider such plume as a disturbance, while in cold conditions some tower designs allow ice to form which may coat the groun or nearby surfaces. Another possible problem is carryover, where salt and other contaminants may be present in the water droplets.

Over time, knowledge of these effects has increased, impacts have been quantified and solutions developed. Technical solutions (such as fish screens and plume eliminators) can effectively mitigate many of these impacts but at an associated cost that scales with complexity.

In a nuclear plant, beyond some minor chlorination, the cooling water is not polluted by use – it is never in contact with the nuclear part of the plant but only cools the condenser in the turbine hall.

On a regional and global scale, less efficient means of cooling, especially dry cooling, will lead to an increase in associated emissions per unit of electricity sent out. This is more of a concern for fossil-fuel plants but arguably carries implications for nuclear as well in terms of waste generated.

On the policy side, one US DOE report notes that a major effect of the US Clean Water Act is to regulate the impact of cooling water use on aquatic life, and this is already driving the choice towards recirculating systems over once-through ones for freshwater. This will increase water consumption unless more expensive and less efficient dry cooling systems are used. This will disadvantage nuclear over supercritica coal, though flue gas desulfurization (FGD) demands for coal will even out the water balance at least to some extent, and any future carbon capture and storage (CCS) will further disadvantage coal.

An August 2010 report from DOE's National Energy Technology Laboratory (NETL) analysed the implications of new environmental regulations for coal-fired plants in the USA. An impending Environmenta Protection Agency rulemaking in February 2011 was expected to mandate the use of cooling towers as “best available technology” to minimise environmental impacts, rather than allowing site-specific assessments and cost-benefit analyses to determine the best option from a range of proven technologies t protect aquatic species. This could mean that all new plants—and perhaps many existing units—need to install cooling towers instead of using once-through direct cooling which do involve a lot of water, but abou 96% of it is returned, slightly warmer. Cooling towers, as well as being more expensive, work by evaporati a lot of water, placing stress on supplies of fresh water – they use 1.8 L/kWh according to the report, compared with less than 0.4 L/kWh for once-through cooling. The NETL report noted that the projected increase in coal-plant water use over the next two decades if direct cooling is no longer allowed on new plants does not factor in the likelihood that many coal plants will add carbon capture and storage (CCS) technology to constrain US carbon emissions, thereby increasing water consumption by a further 30-40%.

A 2010 study by the Electric Power Research Institute (EPRI) found that the total cost of retrofitting US power plants with cooling towers would exceed $95 billion. The cost for 39 nuclear power plants (63 reactors) alone would be almost $32 billion. EPRI’s study encompassed 428 US power plants with once-through cooling systems which were potentially subject to revised US Environmental Protection Agency regulations ostensibly to protect aquatic life from being caught up in the cooling water intake structures. As noted above, under proposed revisions to the Clean Water Act, EPA could mandate that closed-cycle cooling is the "best available technology" to minimise adverse environmental impact to aquatic life. EPRI’s study considered capital costs, revenue losses from extended outages required to change the systems, ar costs associated with losses in plant efficiency including increases in energy use for fans and pumps in closed-cycle cooling systems. Such a change would cost $305 per head for 311 million US citizens to retrofit all once-through cooling system power plants "in order to remedy a virtually nonexistent environmental impact, according to scientific studies of aquatic life populations at these plants," according the Nuclear Energy Institute, the US industry association.

In France, all but four of EdF's nuclear power plants (14 reactors) are inland, and require fresh water for cooling. Eleven of the 15 inland plants (32 reactors) have cooling towers, using evaporative cooling, the other four (12 reactors) use simply river or lake water directly. With regulatory constraints on the temperature increase in receiving waters, this means that in very hot summers generation output may be limited.

In the USA plants using direct cooling from rivers must reduce power in hot weather. TVA's three Browns Ferry units operate at 50% while river temperature is over 32°C.

With one exception, all nuclear power plants in the UK are located on the coast and use direct cooling. In the UK siting study of 2009 for nuclear new build, all recommendations were for sites within 2 km of abundant water – sea or estuary.

An Australian study proposing renewables (wind and solar) for a site in South Australia suggests the figur of 0.74 GL/yr water use for cleaning mirrors (heliostats) on a CSP plant of 540 MW total, 2810 GWh/yr, hence 0.26 L/kWh.

In comparing water demands of nuclear with coal-fired plants consideration needs to be given to water us apart from cooling. There is often a lot of water used in coal cleaning and handling and in ash removal. Th is prone to cause pollution, as is run-off from coal stockpiles.

Future implications of cooling requirements for nuclear power

Fresh water is a valuable resource in most parts of the world. Where it is at all scarce, public opinion supports government policies, supported by common sense, to minimise the waste of it.

Apart from proximity to the main load centres, there is no reason to site nuclear power plants away from a coast, where they can use once-through seawater cooling. Coal plant locations need to have consideration for the logistics of fuel supply (and associated aesthetics), with over three million tonnes of coal being required per year for each 1000 MWe plant.

"Water consumption by nuclear plants is significant, but only slightly higher than water consumption by coa plants. Nuclear plants operate at a relatively lower steam temperature and pressure, and thus lower cycle efficiency, which in turn requires higher cooling water flow-rates. Coal plants, with higher efficiency, can be cooled with slightly less water" per unit of output, but the difference is small.*

* Cooling Water Issues and Opportunities at US Nuclear Power Plants, Oct 2010, INL/EXT-10-2028.

If any thermal power plant – coal or nuclear – needs to be sited inland, the availability of cooling water is a key factor in location. Where cooling water is limited, the importance of high thermal efficiency is great, though any advantage of, say, supercritical coal over nuclear is likely to be greatly diminished due to water requirements for FGD.

Even if water is so limited that it cannot be used for cooling, then the plant can be sited away from the load demand and where there is sufficient water for efficient cooling (accepting some losses and extra cost for transmission[14]).

Generation III+ nuclear plants have high thermal efficiency relative to older ones, and should not be disadvantaged relative to coal by water use considerations.

Considerations of limiting greenhouse gas emissions will, of course, be superimposed upon the above. US DOE figures show that CO2 capture will add 50-90% to water use in coal and gas-fired plants, making the former more water-intensive than nuclear.*

* “Water Requirements for Existing and Emerging Thermoelectric Plant Technologies” DOE/NETL-402/080108, August 2008.

A further implication relates to cogeneration, using the waste heat from a nuclear plant on a coastline for MSF desalination. A lot of desalination in the Middle East and North Africa already uses waste heat from o and gas-fired power plants, and in future a number of countries are expecting to use nuclear power for this cogeneration role. See also WNA Nuclear Desalination information paper.

APPENDIX: Comment on US reports

It is evident that apart from heat discharged with combustion gases from a coal-burning plant and any difference in thermal efficiency which affects the amount of heat to be dumped in the cooling system, there is no real difference in the amount of water used for cooling nuclear power plants, relative to coal-fired plants of the same size. However, some US studies quote a significant difference between coal and nuclea plants, this evidently being related to the (unstated) thermal efficiency of selected examples. The studies exclude nuclear plants on the coast, which employ salt water for cooling.

The March 2002 EPRI Technical Report: *Water and Sustainability (volume 3): US Water Consumption for Power production - the next half century* aims to estimate future water consumption associated with power generation in the USA to about 2020. It uses some "typical" figures for water withdrawal and consumption which show marked differences between coal and nuclear, without giving the source of these or explaining their magnitude. It focuses on freshwater only, and ignores plants with seawater cooling. Its conclusions ar presented on a regional basis in the light of projected increased generations and likely changes in generation technology such as from coal to combined cycle gas.

EPRI points out that this 2002 report is superseded by a 2008 one: Water Use in Power Generation, but th is not readily available. The 2002 and 2008 reports are both based on examples in public data and EPRI databases that provide cooling water usage and heat rejection information for multiple facilities. The numbers provided in these reports and the bar chart above are broadly representative of the water use requirements. The EPRI-derived numbers have consistently been about 10% lower than similar numbers provided by DOE, since DOE uses a theoretical calculation for deriving their water use numbers, rather tha averaging actual plant data, as in the EPRI approach.

Other reports on estimating fresh water needs are from the US Department of Energy's National Energy Technology Laboratory, in 2006, with a 2008 update, and a more general one in 2009. The first two look o to 2030 and use five cooling scenarios applied to regional projections for additions and retirements. Here the assumptions for future coal plants are 70% supercritical[13] and 30% subcritical, the former having ver high thermal efficiency, beyond that of any Generation III nuclear plant. However, coal plants are assumed to need flue gas desulfurization (FGD), which usually increases water use.

Cooling water requirements for each type of plant were calculated from NETL data and are tabulated as follows for "model" plants' consumption of fresh water:

Coal, once-through, subcritical, wet FGD	0.52 litres/kWh
Coal, once-through, supercritical, wet FGD	0.47 litres/kWh
Nuclear, once-through, subcritical	0.52 litres/kWh
Coal, recirculating, subcritical, wet FGD	1.75 litres/kWh
Coal, recirculating, supercritical, wet FGD	1.96 litres/kWh
Nuclear, recirculating, subcritical	2.36 litres/kWh

The figures are puzzling in that supercritical coal should use significantly less than less-efficient subcritical coal-fired plants, and for recirculating use of cooling towers the large difference between subcritical coal ar nuclear is unexplained. Clearly there are significant variables which are not accounted for though they mus surely be relevant to NETL's projections.

The 2009 DOE/NETL report shows a diagram (Fig 3-6) citing the 2002 EPRI report giving net consumptior using cooling towers of 2.27 to 3.8 L/kWh for nuclear*. This is a lot more than that of the figures in the subcritical coal-fired diagram with FGD (Fig 3-2) - 1.9-2.5 L/kWh (0.505-0.665 gal/kWh) with similar blow-down.

* cooling water make-up of 3.0 to 4.1 L/kWh (0.8-1.1 gal/kWh), less blow-down of 0.06-0.20 gal/kWh.

Another diagram (Fig 3-1) citing EPRI 2002 gives net 2.7 L/kWh (0.72 gal/kWh) for nuclear and 2.0 L/kWh (0.52 gal) for subcritical coal. In explanation the text says: "Nuclear plants have a higher cooling tower loac relative to net power generation. This is because the steam conditions are limited by metal brittleness effects from the nuclear reactor thereby reducing efficiency." However, neither it nor the EPRI report justify the large difference, which should be directly related to the stack heat loss in coal plants and to thermal efficiencies.

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[1] At theoretical full efficiency and considering only the vapour phase this is known as the Carnot cycle. Tl Carnot efficiency of a system refers to the difference between input and output heat levels and is more generally referred to as thermal efficiency.

[2] This thermodynamic process of turning heat into work is also known as the Rankine Cycle, or more colloquially as the steam cycle, which can be considered a practical Carnot cycle but using a pump to retu the fluid as liquid to the heat source.

[3] The function of the condenser is to condense exhaust steam from the steam turbine by losing the laten heat of vaporisation to the cooling water (or possibly air) passing through the condenser. The temperature

of the condensate determines the pressure in that side of the condenser. This pressure is called the turbin backpressure and is usually a partial vacuum. Decreasing the condensate temperature will result in a lowering of the turbine backpressure which will increase the thermal efficiency of the turbine. A typical condenser consists of tubes within a shell or casing.

There may be primary and secondary circuits, as in pressurized water reactors (PWRs) and two or three other types. In this case the primary circuit simply conveys the heat from reactor core to steam generators and the water in it remains liquid at high pressure. In a boiling water reactor and one other type, the water boils in or near the core. What is said in the body of the paper refers to the latter situation or the secondar circuit, where there are two.

[4] Within a nuclear reactor water or heavy water must be maintained at very high pressure (1000-2200 ps 7-15 MPa) to enable it to remain liquid above 100ºC, as in present reactors. This has a major influence on reactor engineering.

A more detailed treatment of different primary coolants is in the *Nuclear Power Reactors* paper.

[5] A US Geological Survey report in 1995 suggested 98% of withdrawal is typically returned to source.

[6] For a given electrical output, because the plant needs to be bigger (for given output @36% 1.78 times much heat needs to be dumped, at 33% 2.03 times as much heat has to be dumped - a 14% difference). I one simply looks at the proportion of heat lost in a particular plant at the two efficiencies the difference is 5 and there is 8% less electricity produced.

[7] For each kWh electrical output, at 33% thermal efficiency 7.3 MJ of heat needs to be dumped. At 36% thermal efficiency 6.4 MJ is dumped. With latent heat of vaporization 2.26 MJ/L, this gives rise to 3.2 litres or 2.8 litres per kWh respectively evaporated if all the cooling effect is simply evaporative. This would

amount to 77 or 67 megalitres per day respectively for a 1000 MWe plant if all cooling were evaporative only. In practice, about 60-75% is evaporative, depending on atmospheric factors.

[8] The 2006 DOE report critiqued below shows 2.9 litres/kWh as typical. Other US sources quote 1.5 L/kWh for once-through direct cooling and 2.7 or 3.0 L/kWh for evaporative cooling towers (eg NEI 2009, note 11; NEI 2012).

[9] On basis of 70% of 255 TWh total produced at water cost of 2.25 litres/kWh (80% of electricity is from coal, mostly using evaporative cooling). A more authoritative estimate puts total evaporative loses at 225 GL/yr for inland power plants (Hunwick 2008).

[10] About 0.25 L/kWh at Kogan Creek, including supplementary small amount of wet cooling, 0.15 L/kWh Milmerran.

[11] 48 fans each 9 metres diameter at Kogan Creek.

[12] In Australia Kogan Creek (750 MWe supercritical) and Milmerran (840 MWe supercritical) coal-fired power stations use dry cooling with ACC, as do Matimba and Majuba plants in South Africa. Kendal in South Africa uses indirect dry cooling system. Dry cooling is apparently also used in Iran and Europe. Sou African experience puts ACC cost as about 50% more than recirculating wet cooling and indirect dry coolir as 70 to 150% more.

[13] These use supercritical water around 25 MPa which have "steam" temperatures of 500 to 600ºC and can give 45% thermal efficiency. Over 400 such plants are operating world-wide. One stream of development for Generation IV nuclear reactors involves supercritical water-cooled designs. At ultra supercritical levels (30+ MPa), 50% thermal efficiency may be attained.

Supercritical fluids are those above the thermodynamic critical point, defined as the highest temperature and pressure at which gas and liquid phases can co-exist in equilibrium, as a homogenous fluid. They hav properties between those of gas and liquid. For water the critical point is at 374C and 22 MPa, giving it a "steam" density one third that of the liquid so that it can drive a turbine in a similar way to normal steam.

[14] In the UK all nuclear plants are on the coast and total transmission losses in the system are 1.5%.

Sources:

UK Environment Agency, 2010, Cooling Water Options for the New Generation of Nuclear Power Stations the UK.
EPRI 2002, Water and Sustainability (volume 3): US Water Consumption for Power production - the next half century, EPRI Technical Report
DOE/NETL 2006: Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements, DOE/NETL-2006/1235
DOE/NETL 2008: Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements, update, DOE/NETL-400/2008/1339
DOE/NETL 2009: Water Requirements for Existing and Emerging Thermoelectric Plant Technologies, DOE/NETL-402/080108
EPRI 2008, Water Use in Electric Power Generation, EPRI Report 1014026.
EPRI 2011, National Cost Estimate for Retrofit of U.S. Power Plants with Closed-Cycle Cooling, EPRI Technical Brief 1022212; and Closed-Cycle Retrofit Study: Capital and Performance Cost Estimates, EPR Technical Report 1022491.
DOE/NETL August 2010, Water Vulnerabilities for Existing Coal-Fired Power Plants, report 1429. DOE/INI 2010, Cooling Water Issues and Opportunities at US Nuclear Power Plants, Oct 2010, INL/EXT-10-2028.
Hunwick, Richard 2008, Australia's Inland Power Stations: reducing their thirst.
OECD Projected Costs of Generating Electricity 2010,
Nuclear Engineering handbook 2010

ESAA, Electricity Gas Australia 2010
IAEA 2012, Efficient Water management in Water-Cooled Reactors, IAEA Nuclear Energy series No. NP-T
2.6.
Nuclear Energy Institute 2009, Water Use, Electric Power, and Nuclear Energy.
Nuclear Energy Institute, Nov 2012, Water Use and Nuclear Power Plants, Factsheet.
ThinkClimate & Brown&Pang, Zero Carbon Options (for Port Augusta power plant), 2012.
