



CURTAILMENT OF NUCLEAR POWER OUTPUT DURING EXTREME HEAT WAVES: THE EUROPEAN CASE

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1. The issue

For the second summer in a row, some nuclear power plants in Europe have been forced to temporarily shut down or reduce power output due to extreme heat waves. Some have suggested that this curtailment demonstrates that nuclear energy is ill-adapted to a warming climate.

Why do some nuclear power plants have to stop producing electricity during heat waves, and what are the implications of this issue? Are there ways to fix the situation? In this article we explore the impact of the European heat waves of 2003, 2006, 2018 and 2019 on nuclear power output.

2. Summary

- Nuclear power plants already operate at the highest capacity factor and availability factor of any electricity generating technology. This is also true during heat waves, when wind and hydroelectric output can be substantially depressed.
- Curtailment of nuclear power during heat waves is not a result of safety considerations. Curtailment primarily occurs at river sited plants and are due to limitations in the allowed temperature at which cooling water can be returned to a river.
- Curtailment of nuclear power due to periods of extreme heat has had the effect of reducing European nuclear power output by approx. 0.1% since the year 2000. For France specifically, which with its many inland river-sited plants has been the worst hit country, the corresponding figure is approximately 0.15%
- At peak times, less than 5% of European nuclear power capacity has been unavailable specifically due to curtailment during recent heat waves. Even at times of peak curtailment, the *availability* of nuclear power exceeded that of any other low-carbon electricity generating technology in Europe, including solar PV, wind and hydroelectricity.
- To address this problem in the near-mid-term, technical fixes are not necessarily required. For example, the French nuclear fleet runs at 60% capacity factor during the summer, heat wave or not, since it is typically deployed to vary with load, and load is lowest in summer, so scheduled outages are common. Electricity prices have remained modest during curtailment periods (€40-60/MWh) and France covers its own demand during the summer. To compensate for lost output at its most vulnerable river-sited plants during heat-wave curtailments, France could increase output at the remainder of its fleet if economic incentives were provided.
- Over the longer term, there are also technical options readily available for *all* types of power plants, including nuclear, to increase both rates of utilization as well as availability. These will also be driven by economics, not engineering limits. The cost increases associated with these options are relatively modest.

3. Utilization of electricity generation capacity

Commercial power plants (of any type) are generally constructed, maintained and operated in a way which maximizes profits for the plant's owners.¹ This rarely, if ever,² means that the plants are configured to produce electricity at their maximum possible output for all hours of the year. A measure of the actual power production relative to the maximum possible power production is called the *capacity factor* (CF) and is measured in percent. A CF of 100% means the power plant operates at maximum capacity all hours of the year, while a CF of 20% means its annual output is one fifth of its theoretically achievable output. The annual capacity factors for the United States in 2018 for all the main electricity production technologies are given in Figure 1.

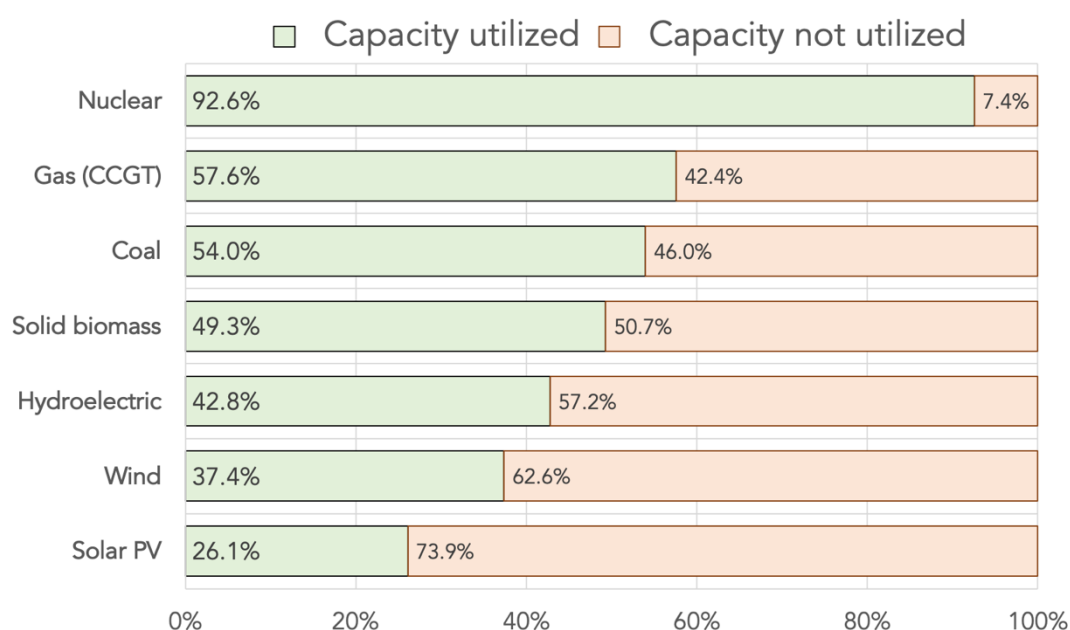


Figure 1, Annual utilization of installed capacity (capacity factor), United States 2018³

As is obvious from Figure 1, there are no rules or regulations forcing electricity generators to always produce at their maximum capacity. Instead, individual power plants make investments that impact capacity factors and availability in a way which maximises their profits.

¹ The construction and operation of all power plants are subject to national and sometimes international regulation and law. Additionally, electric grid operators and environmental agencies may impose operational restrictions to the way plants are build and operate.

² Smaller hydroelectric power stations located in river segments with very abundant and steady water supply may in theory approach close to 100% capacity factors during prolonged periods but will eventually require going offline for maintenance. Some modern geothermal plants have also been known to have years at close to 100% capacity factor.

³ US Energy Information Administration (2019)

4. Availability of electricity generation

While there are no incentives or rationale for all generators to be configured to always produce at their maximum capacity, this is not the same as saying that none of them *could do so*. Obviously, wind and solar plants are at all times limited by the resource that powers them, and therefore can never be called upon at will to increase production when needed. The “availability” of solar power, defined as the output one can reliably expect to see at any one hour of the year, is 0%. This is due to the complete unavailability of solar power at night.⁴ While similarly one cannot guarantee any production from wind power, *completely* still periods over large areas of land and sea are quite rare. Since there is usually *some* wind power available in a geographically dispersed and large system, wind power in aggregate is typically assigned a reliability estimate of 3-10%⁵. This means that system planners “expect” that 3-10% of the possible production from wind turbines (in aggregate across the system, not single generators) is available at any one time.

For power plants that use some kind of fuel or stored water as the energy input, the situation is very different. As long as sufficient fuel is kept available on site, there are in general⁶ no technical limitations that keep such plants from being able to produce at maximum capacity when called upon, at least during shorter periods. Typically, power sources such as coal, gas, oil and biomass (bundled as “combustion”), conventional hydroelectric and nuclear power are assigned an availability figure of up to ~90%.

Extreme heat-waves reduces the availability of *all types of electricity production*, and also has negative impacts on the availability of the electricity grid itself. Hydroelectric power plants can suffer from severe droughts and general unavailability of water. All thermal power plants, including nuclear power plants, operate at reduced thermal efficiency as the water and air heats up, and local regulations may force curtailments at some plants. Solar panels operate at reduced efficiency at very high air temperatures. Wind power output can drop dramatically during heat waves for extended periods of time, as was seen most recently this summer in Europe.⁷ A representative availability span (which depends on local conditions) is given in Figure 2.

⁴ Solar power in aggregate in a hypothetical electricity grid with extreme longitude spread (across many time zones) may in theory be assigned a higher than zero availability figure.

⁵ This value can be calculated and estimated in different ways, one of which is calculate an output duration curve and assign the reliable output fraction as one which is, for example, reached more than 90% of the hours of the year.

⁶ Again, this report will highlight the exceptions to this generalization.

⁷ Overall, some models have suggested that wind availability in the Northern hemisphere may decrease by as much as 15% due to future warming. See Karnauskas, Kristopher B., Julie K. Lundquist, and Lei Zhang. "Southward shift of the global wind energy resource under high carbon dioxide emissions." *Nature Geoscience* 11.1 (2018): 38.

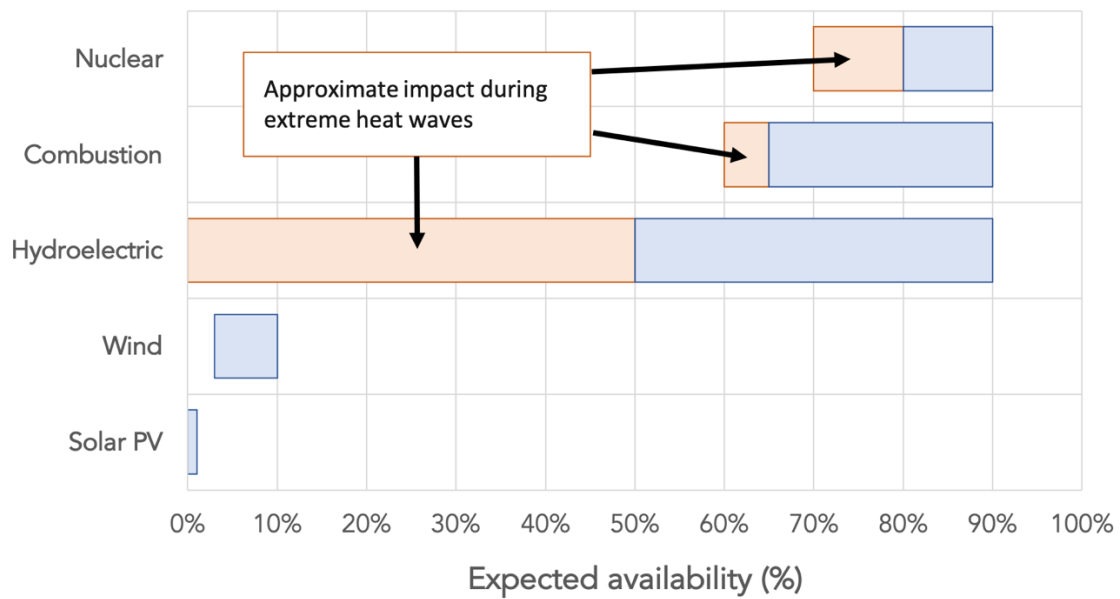


Figure 2, Representative span of availability for different power sources

European wind energy output, shown in Figure 3, typically dips to its lowest values during summer. Averaged over the entire summer of 2018, the total combined wind energy availability across all EU member states was about 14%.

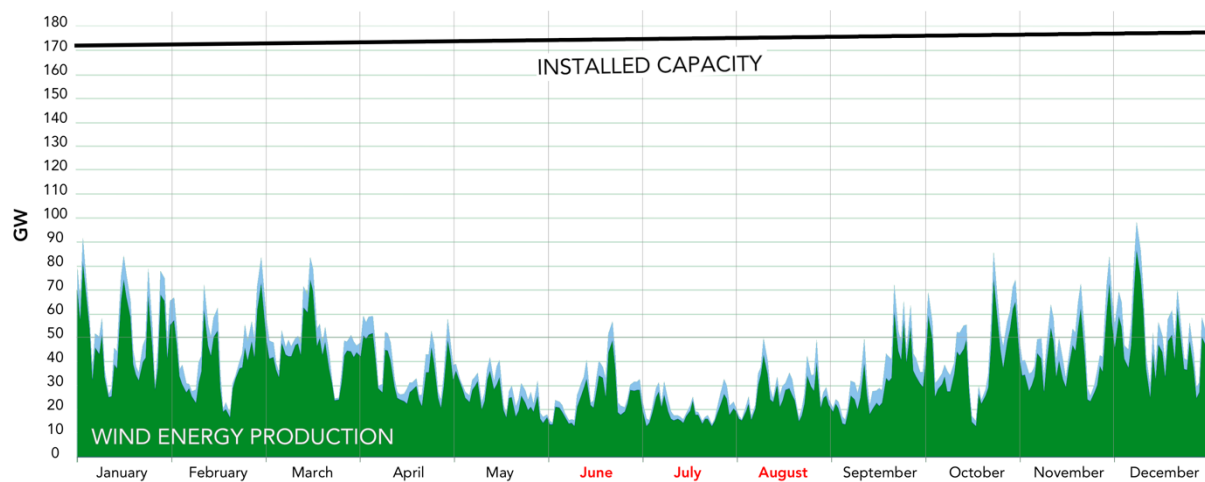
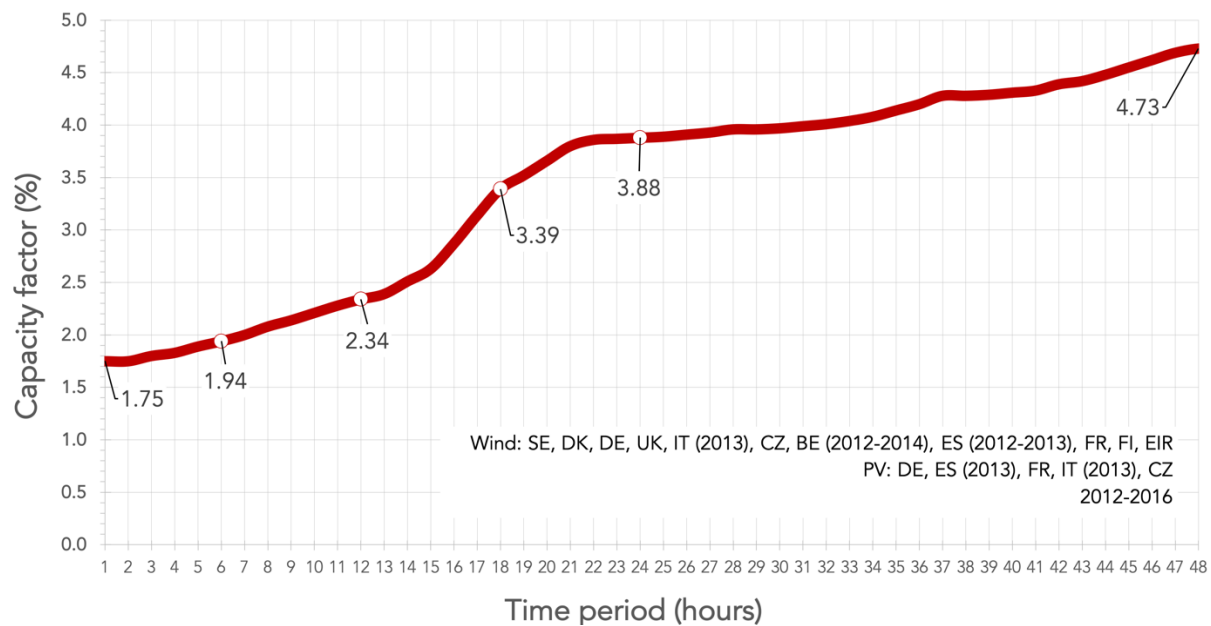


Figure 3, Wind Energy output and installed capacity in Europe (EU member states) in 2018⁸

Averaged over shorter time durations and smaller geographical areas, the minimum availability of intermittent energy sources such as wind and solar PV drops further. Historic production statistics shown in Figure 4 indicate that the minimum combined output of all wind and solar power in Europe can drop below 2% during single hours, and below 5% for periods as long as 48 hours. Minimum combined shorter-term output periods typically occur

⁸ Data from Wind Europe, "Wind energy in Europe in 2018 Trends and statistics" (2019). Installed capacity is assumed to be linearly increasing from start to end of year values, actual trend may differ.

in the summer nights and longer-term minimum output typically occurs in early fall (September and October).



*Figure 4, Minimum combined capacity factor of Solar and Wind energy in Europe
 (based hourly data 2012-2016 from national TSOs and ENTSO-E)*

The availability of nuclear and hydroelectric power plants is also seasonally dependent, rising to peak values (~90%) during times of peak electricity demand. Since availability is typically less important during seasons of low demand, their availability in aggregate is, *by planning*, lower. Nuclear plants in Europe schedule their annual outage for maintenance and refuelling during late spring, summer and early fall, when electricity demand is the lowest. Similarly, hydroelectric plants with large reservoirs operate at low capacity during these periods in order to save water for higher demand periods in the winter. Scheduled outages can be shifted in time to increase both production and availability to specifically tackle heat waves, if this is deemed necessary.

For example, the French nuclear fleet runs at ~60% capacity factor during the summer, heat wave or not, since it is typically deployed to vary with load, and load is lowest in summer, so scheduled outages for refueling are common. French electricity prices have remained modest during curtailment periods (€40-60/MWh) and France covers its own demand during the summer. Therefore, to compensate for lost output in its river-sited plants, France could increase output at the remainder of its fleet or alter its scheduled outage planning if sufficient economic incentives were provided. An approximate comparison between the summertime nuclear availability, planned unavailability and the impact of heat-wave curtailment compared to French summertime electricity demand is given in Figure 5.

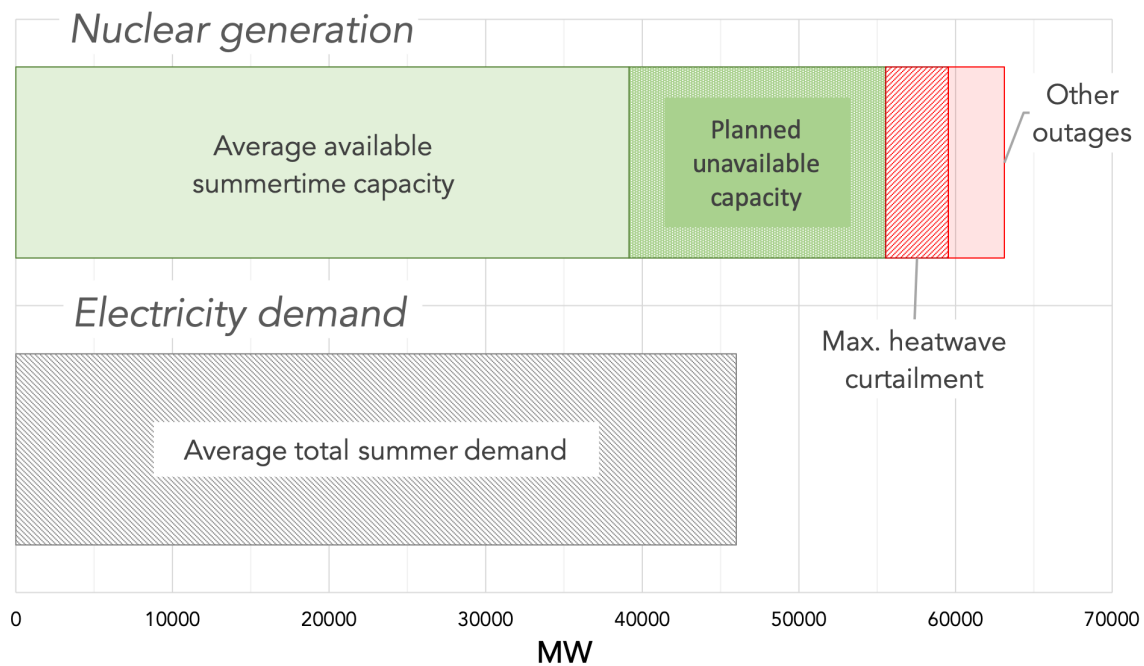


Figure 5, Comparison between electricity demand, available nuclear capacity, planned unavailable nuclear capacity and heatwave curtailment in France in summertime

5. Options to increase utilization and availability

5.1. Introduction

There are technical options readily available for *all* types of power plants to increase both rates of utilization (raising the capacity factor) as well as availability. However, absent specific regulations, if the plant does not increase profits by investments that raise the capacity factor or availability factor, such investments will not be made.

5.2. Wind power

Wind power capacity factors are physically limited by the local availability of wind. A wind turbine with a very high hub height, very long blades and a small generator capacity will produce at a far higher capacity factor than one with a shorter hub height, larger capacity generator and shorter blades. Some wind turbine manufacturers have taken modest steps in this direction, producing what is referred to as “low specific power designs.” In theory, one could design a wind turbine that produces electricity near rated power even at *very* low wind speeds, but such designs would increase costs.

5.3. Solar power

Solar power plant capacity factors are physically limited by insolation, but this can still be adjusted by system design. Solar panels produce direct current (DC), which is then inverted in to alternating current (AC) to be fed to the electric grid. Typically, the installed DC capacity of the solar panels is higher than the inverter AC capacity by a factor of 1.1-1.3 (this is called the “load ratio”). Systems are designed this way because it is not economically justifiable to invest in an inverter and grid connection to handle the absolute peak DC load, which may occur just briefly in the middle of the day. A very high load ratio has the effect of raising the solar capacity factor (which is based on inverter AC capacity) while reducing total electricity fed to the grid. General availability is not increased unless storage is added, since there is still no production at night.

5.4. Hydroelectric power plants

The output of a hydroelectric power plant is limited to the annual in-flow of the river system to which the plant is connected. For a run-of-river plant (where dams do not regulate flow to any important degree), raising the capacity factor and availability is technically very simple. Run-of-river plants with turbines and generators sized to match the expected annual minimum flowrate of the river section where the plant is sited would achieve a very high capacity factor and availability. This type of capacity derating would however dramatically reduce electricity generation and the economic viability of such plants.

5.5. Nuclear power and other thermal power plants

Nuclear power plants typically rank at or near the top of all available options for both capacity factor and availability in most places where they are present, but there is still room for improvement. At certain river-sited power stations, power output occasionally needs to be reduced, and some plants need to shut down entirely during extreme heat events. Since these events occur very infrequently and typically only lasts for a few days, it has not been deemed cost-effective to make the investments required to be able to carry on producing at maximum capacity during such events. The lost income from reduced electricity sales during a few days in the summer every few years may be less than the expenses incurred from investments required to avoid foregoing this production. In this sense, the situation is exactly the same as the lacking economic motivation to further increase availability and utilization of wind, solar and run-of-river hydroelectric power.

6. Nuclear power output during heatwaves

For nuclear and other thermal power plants (coal, combined-cycle gas, oil, biomass etc.) situated at inland river locations, the availability and temperature of cooling water may give rise to problems during extreme heat waves. In such cases, the power plants may have to reduce their power output or temporarily stop production.

Curtailment of nuclear power during heat waves is not a result of safety limitations. This is instead usually in response to environmental regulations which limit the temperature at which the plant is allowed to return cooling water to a river.⁹ Coastal power plants are generally unaffected by extreme heat wave events due to the more limited impact temporary heat waves have on the temperatures of larger bodies of water such as a large lake or ocean.

Since 2000, there have been four major heat-wave events where nuclear power plant output has been significantly curtailed: in the summers of 2003, 2006, 2018 and 2019¹⁰. France, the largest nuclear power producer in Europe and second globally (behind the US), has been hardest hit. This is mainly because the French nuclear fleet has a large number of plants sited at inland river locations. The heat wave of August 2003 was exceptional in its duration, intensity and extension and caused temporary curtailed output at 30 nuclear reactors across Europe. The heat waves of 2006, 2018 and 2019 mainly impacted French plants. Apart from plants in France, heat-wave curtailment of significance after 2003 is known to also have occurred at the Ringhals-2 reactor in Sweden¹¹, the Loviisa plant in Finland, the Mühleberg & Beznau plants in Switzerland, the Santa Maria de Garona plant in Spain and the Isar, Brokdorf & Grohnde plants in Germany. French nuclear output has in total been reduced by approximately 12 TWh due to extreme heat-wave curtailment since 2000, which corresponds to about 0.14% of total nuclear output during the same period. Actual output and heat-wave curtailment is shown in Figure 6.

⁹ However, if there exists an urgent need for electricity production, regulatory bodies are sometimes willing to grant a temporary exemption from the cooling water temperature restrictions. During the heatwave in August of 2003, three reactors at the Tricastin plant and one at the Golfech plant in France operated for ten days under cover of these temporary provisions to avoid supply disruptions.

¹⁰ Some very *minor* curtailment is known to have occurred in other years, for example in 2015.

¹¹ Of the curtailment events that have been described, forced reductions in coastal power plant output are exceptionally rare, but examples do exist. In late July 2018, the power of the coastal-sited Ringhals-2 reactor in Sweden was temporarily curtailed to 49% due to sea temperatures going above 25°C. This is the only known occurrence of a Swedish reactor reducing power output due to sea water temperature. Due to this curtailment, around 85 GWh of possible production was lost, which corresponds to 0.1% of Swedish nuclear power output that year.

Table 1, Estimated nuclear power plant curtailment due to heat waves in Europe

Heat-wave	Curtailed nuclear output due to heat-waves (TWh)		
	France	Rest of Europe ¹²	Total
2003	5.5 ¹³	2-3	7.5-8.5
2006	2.5	0.5-1.0	3-3.5
2018	1.7 ¹⁴	0.3-0.6	2-2.6
2019	1-2	0.2-0.5	1.2-2.5
Other years	0.3	0.2	0.5
Sum	11-12	3.2-5.3	14.2-17.3

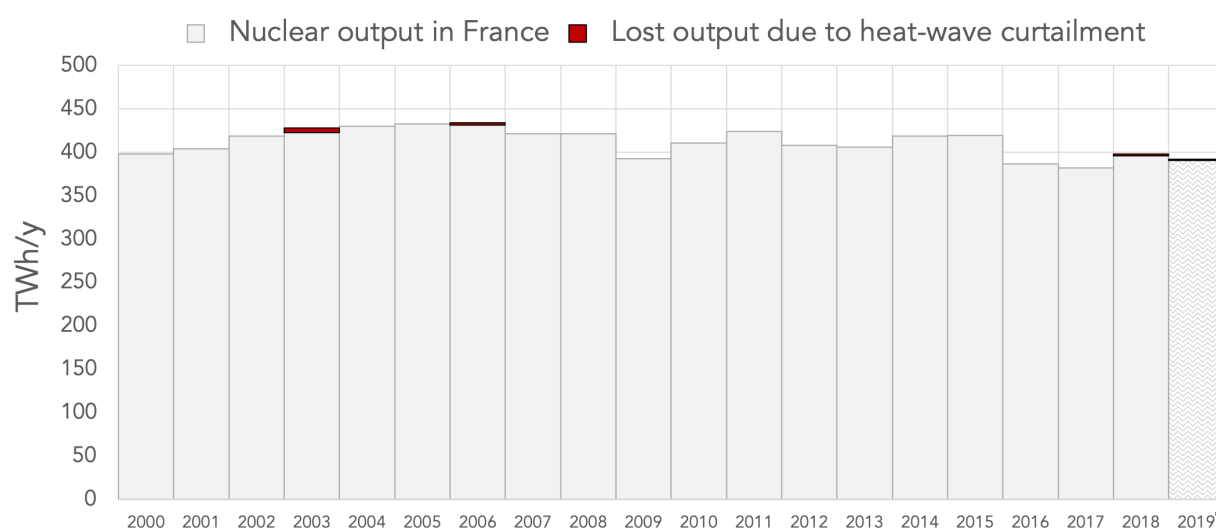


Figure 6, Actual nuclear power plant output and approximate lost output due to heat-wave curtailment in France (2000-2019) [preliminary figures for 2019]¹⁵

Outside of France, the majority of nuclear power plants are located on less sensitive rivers, large lakes or at the coast, so the relative impact of heat-wave curtailment is significantly smaller. An estimation of the impact of extreme heat-wave curtailment on total nuclear power plant output in Europe is given in Figure 7. The total lost output during the period shown is approximately 0.1%.

¹² This is a rough estimate based on news reports about curtailments

¹³ SFEN "Adapter les centrales nucléaires au changement climatique" (2015)

¹⁴ 1.7 TWh is according to this report: <https://www.montelnews.com/en/story/intense-heatwaves-no-longer-a-threat-to-nuclear-fleet--edf/1021785>, actual calculated lost output from French unavailability data is 0.1 TWh. The reason for the difference is not clear.

¹⁵ BP Statistical Review of World Energy 2019, SFEN "Adapter les centrales nucléaires au changement climatique" (2015) and Nucleonics Week 60 (2019). Nuclear output numbers converted to net figures by subtracting 4.1% self-consumption of electricity. 2019 output figures are estimated from production data until June 2019 and compared with previous years of output.

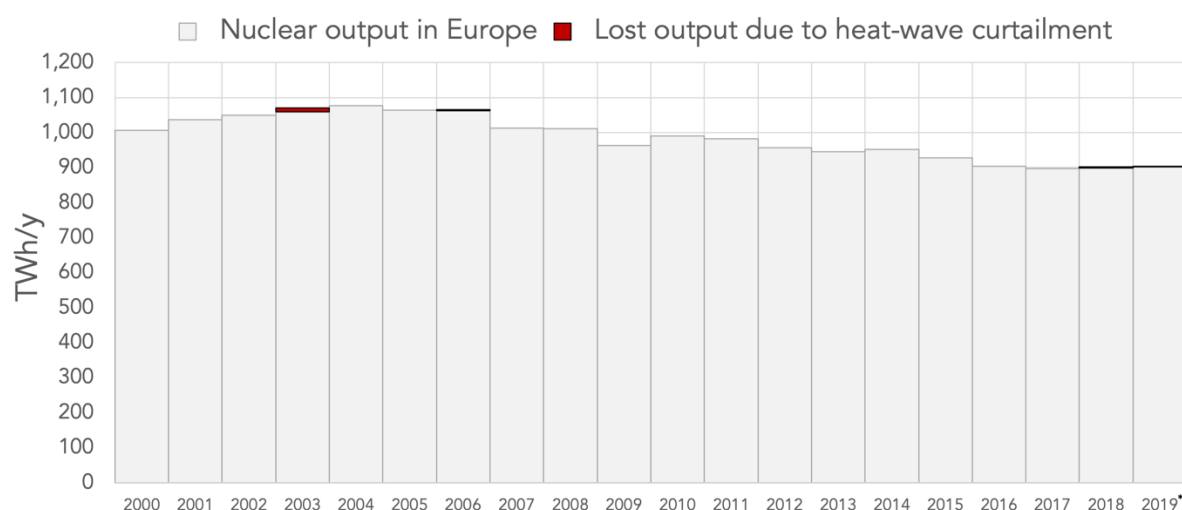


Figure 7, Actual nuclear power plant output and approximate lost output due to heat-wave curtailment in Europe (2000-2019) [preliminary figures for 2019]¹⁶

While lost generation is marginal compared to annual output, the larger worry is the availability of the power during the hours and days where reliable electricity is critical. The unavailability of nuclear power in Europe due to heat wave curtailment has momentarily exceeded 5 GW, or about 4% of the Europe’s installed nuclear power. However, French nuclear energy output and availability during years of heat waves and curtailment do not differ noticeably from years without severe heat events, as can be seen in Figure 8. Summer-month output of nuclear energy was in fact 2.1-2.7% higher in 2018 (when heat-wave curtailment occurred) compared to the preceding two years.

¹⁶ BP Statistical Review of World Energy 2019, SFEN “Adapter les centrales nucléaires au changement climatique” (2015) and Nucleonics Week 60 (2019). Nuclear output numbers converted to net figures by subtracting 4.1% self-consumption of electricity. 2019 output figures are estimated from production data until June 2019 and compared with previous years of output.

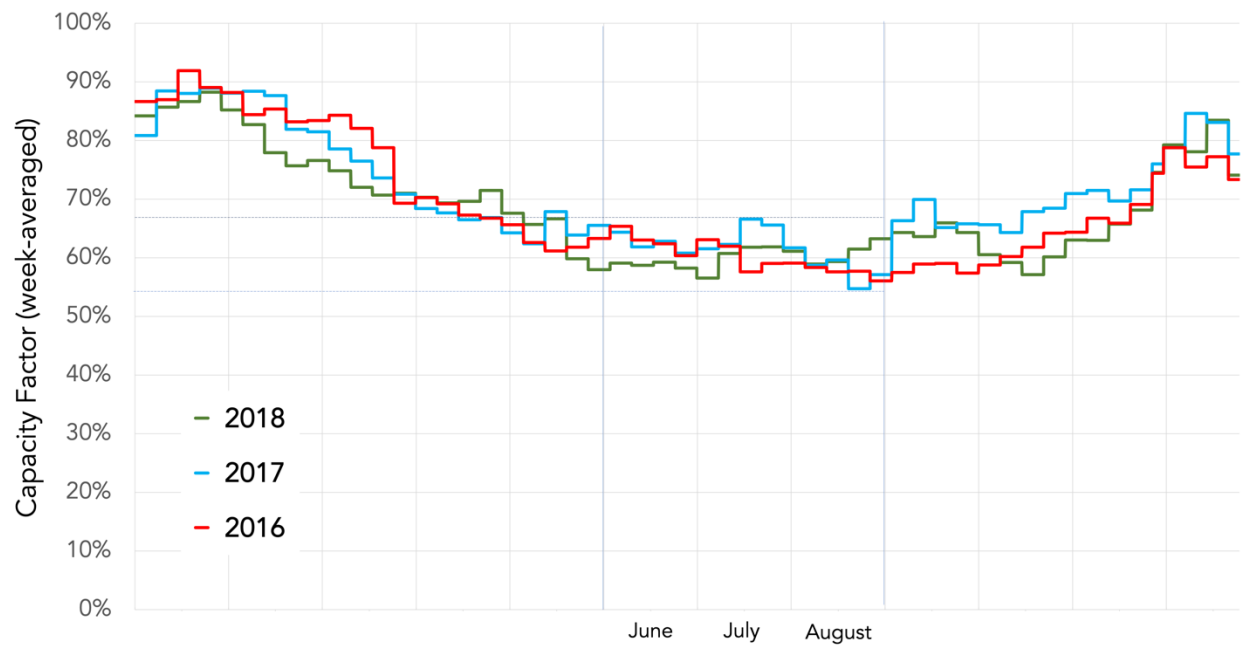


Figure 8, Weekly capacity factor of French nuclear energy for 2016, 2017 and 2018

Figure 9 gives the power output in 30-minute increments of the French nuclear fleet during the summer of 2018 compared to the span of values from the five preceding summers during which there were no extreme heat events and no curtailment. The output is within the bounds of the typical output during summer, and again no discernible impact is seen during the curtailment period.

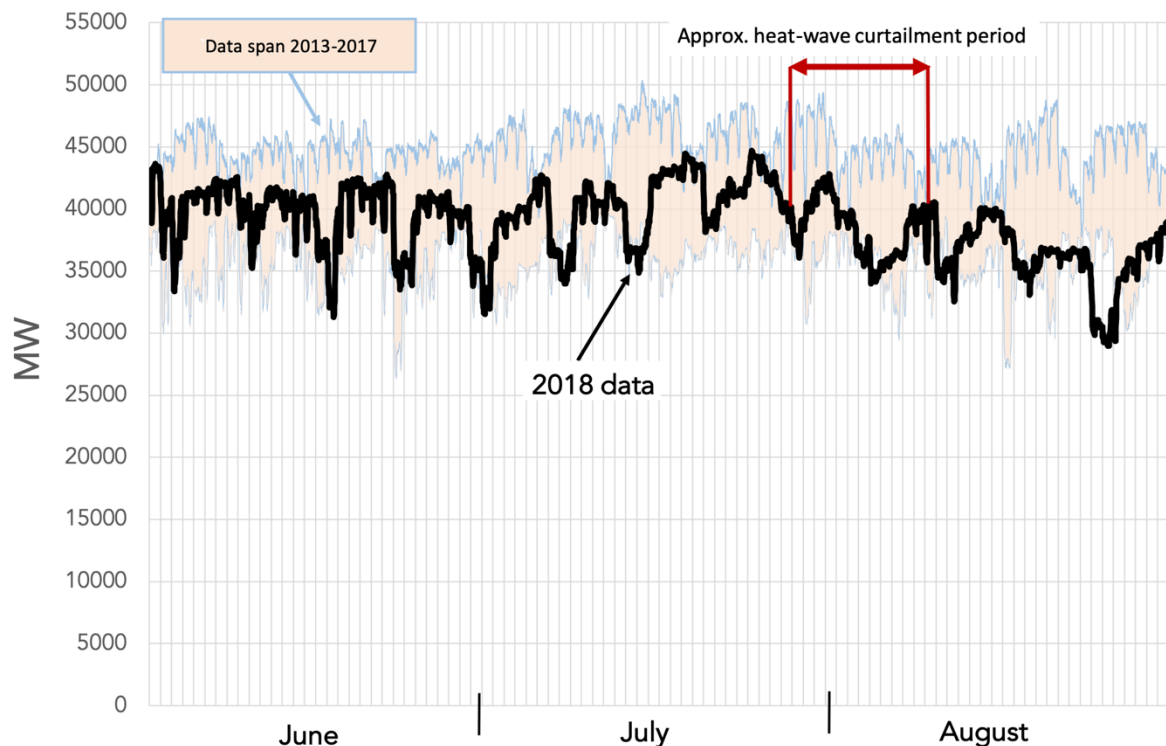


Figure 9, Comparison of French nuclear output during an extreme heatwave-stricken year (2018) and five years without extreme heatwaves (2013-2017)

The capacity factor duration curve of low-carbon electricity sources in France during the extreme heat-wave summer of 2018 is shown in Figure 10. Although nuclear was struck by heat-wave curtailment that summer, it still shows a steadier and more reliable power output (i.e. “flatter”) duration curve than the other available low carbon electricity options. Another way to show this is by scaling up solar and wind output across this summer to the level of actual nuclear output. Figure 11 shows French solar PV scaled up to provide the ~86 TWhs of electricity that nuclear provided in the summer of 2018. Power output in this example varies between zero and 135 GW, to provide the average output of ~39 GW. Wind power has been scaled in the same way in Figure 12, and shows an output variation between 1.4 GW and 158 GW. Figure 12 shows that depressed output of wind can last over week-long periods. A hypothetical blend of 50% wind and 50% solar scaled to nuclear output across the summer is seen in Figure 13. The combined wind and solar output vary between 3 GW and 117 GW and can remain low over multiple week periods.

Thus, while heat-wave curtailment of nuclear power plants does reduce its availability and reliability as a power source, this impact is relatively small when compared to the inherent variability of output in other low-carbon electricity options.

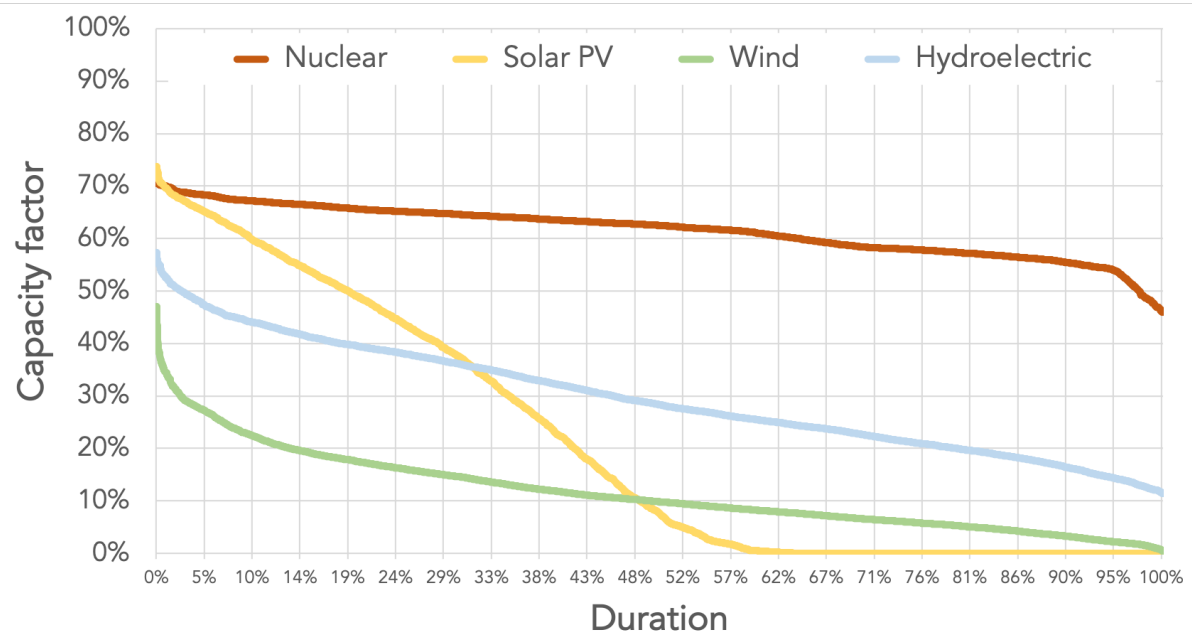


Figure 10, Duration curve for capacity factor of low-carbon electricity in France during the summer of 2018 (June 1st to August 31st)

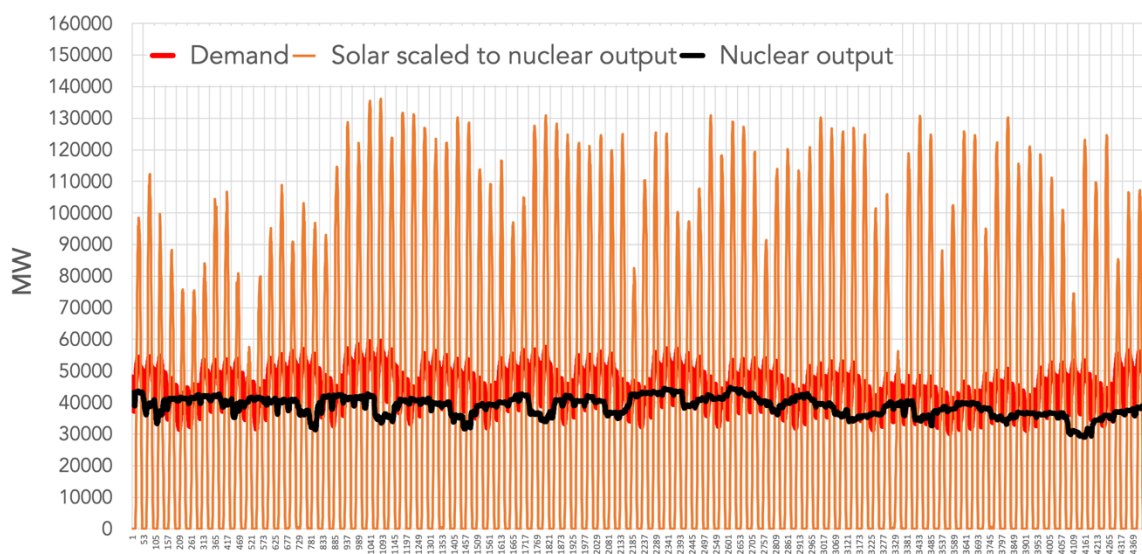


Figure 11, French Solar PV output scaled to nuclear output across the summer of 2018

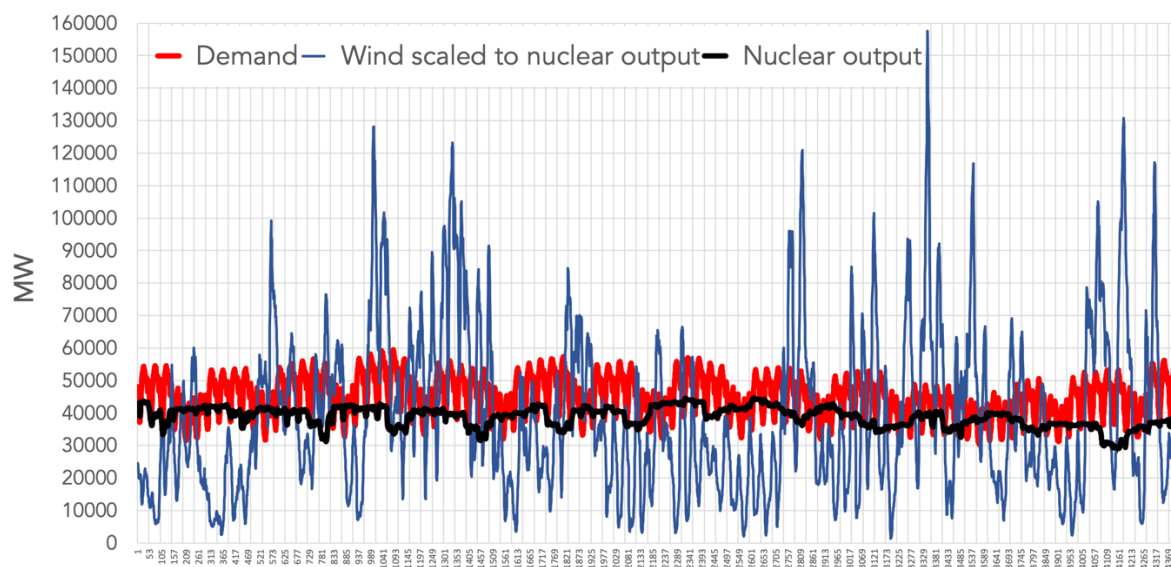


Figure 12, French wind power output scaled up to nuclear output across the summer of 2018

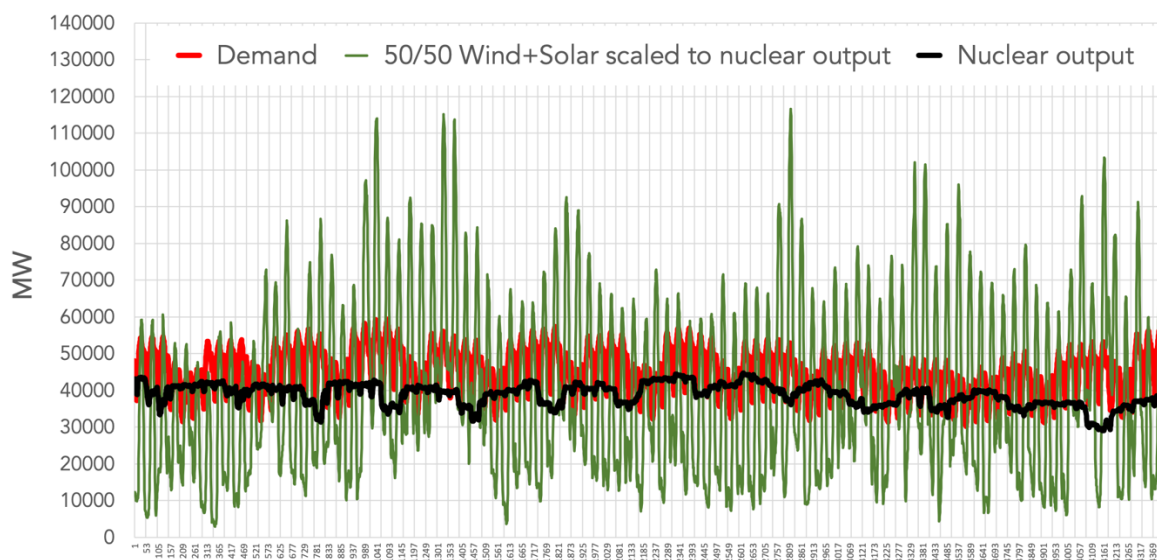


Figure 13, French wind and solar power output scaled up to combined match nuclear output across the summer of 2018

7. Avoiding curtailment

7.1. Introduction

It is obvious from the data presented in previous sections that heat-wave curtailment is currently a marginal issue with a very low economic impact on nuclear power production. However, changes in the global climate make extreme weather events more likely going forward. It is telling that out of the 4 recent periods in which significant curtailment has occurred in Europe since 2000, two occurred in the last two years. With increasing likelihood of curtailment in the future, the economic case for investments to overcome these problems becomes more appealing. At present levels, which indicates a medium-term loss of production of $\sim 0.1\text{--}0.15\%$ /year, only relatively minor (and cheap) modifications can be justified to mitigate the situation. However, regulatory requirements as well as public relations pressure may induce nuclear power plant operators to nonetheless make significant investments to overcome these issues even in the near term.

In response to the curtailments of 2003 and 2006, Electricité de France (EDF) launched the "Grands Chauds" ("Great Heat") project. This project examines the prospects for climate change, analyses the impact on the French nuclear power fleet and defines the necessary adaptations both for safety and availability. Reference plant design temperatures have been adapted, site by site, for both air and water. For example, at the peak of the most extreme heat event to date (that of August 2003), temperatures of the Loire river that cools the Chinon nuclear power plant were as high as 32.5°C . At the Tricastin plant, the highest ever recorded air temperature (also in 2003) was 42.5°C . Going forward the Chinon plant will be adapted to manage a water temperature of 37°C in the Loire river, while the Tricastin plant should handle air temperatures of 46°C . In general, the plants involved in the Grand Chauds program have had their design temperatures updated to be $3\text{--}5^{\circ}\text{C}$ above the peak temperatures ever recorded in the air and water at these sites. Given that extreme weather events are likely to become ever more extreme and frequent, it is not guaranteed that such modifications will preclude any curtailment in the future. However, with the program in place, the relative frequency and importance of curtailment are likely to fall.

7.2. Upgrades to existing plants

7.2.1. Options for existing coastal nuclear power plants

The documentation and analysis for the operation of the components and systems of nuclear power plants are defined for some specific maximum temperature of the air and sea or river water. For many plants, the original analysis and determination of these “reference temperature” values were done in 1970s and 80s and may therefore not be applicable for the peak temperature conditions of the 2000s and beyond.

While the Swedish coastal-sited Ringhals-2 was temporarily forced to reduce power, no curtailment was needed at the adjacent Ringhals 1, 3 and 4 reactors at the same site. The only difference of note is that at Ringhals-2, the documentation for one of the cooling circuits only extended to cases of water temperatures up to 25°C. Relatively minor work, which may in fact be limited to simply reanalysing and resubmitting documentation for one subsystem, would be needed to raise the full-power maximum sea water temperature to 27°C, in line with the rest of the Ringhals reactors.

One engineering option to future-proof any coastal plant while also increasing power output is to install a deepwater intake for cooling water. Rather than taking water from near the surface, cooling pipes are extended down to deeper and cooler waters, where temperatures are consistently cold even during heatwaves. Such an adaptation would cost approximately \$100 million for a 1 GWe plant and is therefore rarely economically justified compared to the lost output it would compensate for.

7.2.2. Options for existing river-sited nuclear power plants

There is a wide array of potential upgrade options to allow for river-sited nuclear power plants to be operated at full power even during extreme heat wave events.

1. Some nuclear plants located on large rivers with high flow rates use open loop (once-through) cooling. These are the types of plants that most commonly face curtailment during heat waves. Adding recirculating wet cooling towers at these sites would reduce water withdrawal from the river by at least 95% and, given enough area available for towers, could be dimensioned in a way as to preclude any future curtailment. The total cost for cooling tower capacity for a 1 GWe output plant is approximately \$100 million.¹⁷
2. Some plants use a combination of open loop and cooling tower cooling, such as the occasionally curtailed Bugey nuclear plant on the Rhone river. A transition to fully

¹⁷ Koen Rademaekers et al., “Investment needs for future adaptation measures in EU nuclear power plants and other electricity generation technologies due to effects of climate change,” European Commission, Brussels, Belgium, 2011.

closed-loop cooling using 2 additional recirculating wet cooling towers would reduce water withdrawal requirements sufficiently to preclude curtailment altogether. If sufficient land area is available, an artificial pond could be added, as has been implemented at the Cattenom plant, which would further reduce the reliance on river water.

3. For hypothetical plants located at sites where no water-cooling of any kind is available, for instance by a *completely* dried up river, dry-cooling options are available. No such sites to be retrofitted exists, but it may be an option for future siting of plants, for example in far in-land China.

The approximate water usage of the different options is given in Table 2.

Table 2, Nuclear plant water use with different cooling options

#	Solution	Water withdrawn from river (m ³ /MWh)	Water evaporated (m ³ /MWh)	Water returned to river (m ³ /MWh)
1	Direct cooling (open loop)	75-230 (1)	~1.5 (2)	(1)-(2)
2	Recirculating wet cooling tower (natural draft)	3.0-4.2	~2.8	0.2-0.8
3	Recirculating cooling pond	1.9-4.2	1.7-3.4	0.2-0.8
4	Dry cooling	0	0	0

8. About the Author

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New York Times Book Review (2019):

<https://www.nytimes.com/2019/02/05/books/review/bright-future-joshua-s-goldstein-staffan-a-qvist.html>

Financial Times Review (2019)

<https://www.ft.com/content/ec785c86-1021-11e9-acdc-4d9976f1533b>

“A Bright Future starts with a bang. “Few books can credibly claim to offer a way to save the world, but this one does,” the psychologist Steven Pinker writes in his foreword. That is a bold assertion, but by the time I had finished the book, I was half-convinced he was right.”