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Can reactors react?

Is a decarbonized electricity system with a mix of fluctuating renewables and nuclear reasonable?

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Summary

In Nov 2017, the French government postponed its plan from 2015 to reduce the share of nuclear from 75% to 50% because it did not believe it could replace the missing 25% with renewables alone; power from natural gas would be needed, thereby increasing carbon emissions. One aspect remains overlooked in the French discussion: the potential inability of the country's reactor fleet to ramp enough in order to make space for significant shares of wind and solar power. This oversight is typical of the current discussion about low-carbon power scenarios in English as well – but not in German.[1]

"Deep decarbonization" has become a buzzword in the energy sector in recent years. How can we achieve a low-carbon energy supply? Mobility is expected to be increasingly electric, as will heating and cooling. The power sector will therefore be more important. Nuclear power is a source of very low-carbon electricity. Yet, markets are focusing on wind and solar, and there are signs that the priority given to them is hurting the profitability of baseload plants, including nuclear. Recent academic studies focusing on climate change mitigation have therefore argued that nuclear should be included along with wind and solar towards creating the most affordable clean power supply.

Germany's nuclear phaseout is partly based on an understanding that baseload cannot flexibly accommodate fluctuating wind and solar,[2] with nuclear being the least flexible of all conventional options. A discussion about this "inherent conflict" (*Systemkonflikt*) took place roughly from 2008-2011; the second phaseout of 2011 put an end to the debate. That phaseout also marked the point when Germany became the focus of international attention; the previous discussion in Germany about the flexibility of nuclear thus went largely unnoticed abroad. This paper summarizes that debate, possibly for the first time in English.

Those calling for a "balanced" mix of nuclear, wind, and solar assume that nuclear reactors can ramp up and down sufficiently to back up wind and solar – when the subject of nuclear load-following is mentioned at all. In a 2016 final report on a symposium entitled "Getting to Deep De-carbonization: What Role for Nuclear Power?", the Bulletin of the Atomic Scientists does not use the words "flexible" or "capacity factor" at all. Ramping and load-following were apparently not discussed (Stover 2016). This omission stands in stark contrast to the focus of the TAB study from Germany discussed below.

[1] The author would like to acknowledge helpful feedback from: Antony Froggat, independent consultant; Raffaele Piria, Adelphi; Ortwin Renn, IASS; Dominik Schäuble, IASS; Sybille Röhrkasten, IASS; Stephen Thomas, PSIRU University of Greenwich (emeritus); and Arne Jungjohann, independent consultant. Any remaining errors are the author's alone.

[2] Most literature in English speaks of "variable renewable energy" (abbreviated as VRE), by which primarily wind and solar are meant. Hydropower, particularly run-of-river dams, can be seasonally variable as well, but this source is not dealt with in this paper because hydropower is small in Germany (around 3.5% of power demand), with no significant further potential. Most importantly, the present author rejects the term "variable," which means "can be adjusted" (as in "variable-speed"). The term "variable" was chosen to avoid confusion with "intermittent," which is also when central-station plants fail. In German, one speaks of "fluktuierende erneuerbare Energien," which is accurate. For that reason, "fluctuating wind and solar" is spoken of in this paper instead of VRE.

When nuclear flexibility is discussed, it is often explained with documentation of single reactors. But a systematic investigation of the demonstrated flexibility of entire nuclear fleets is what matters if nuclear is to complement wind and solar. This paper investigates the issue and finds that the French and German reactor fleets – held to be the most flexible worldwide[3] – do not seem to have ever ramped by more than a third in a day, which is less than gas and coal.[4]

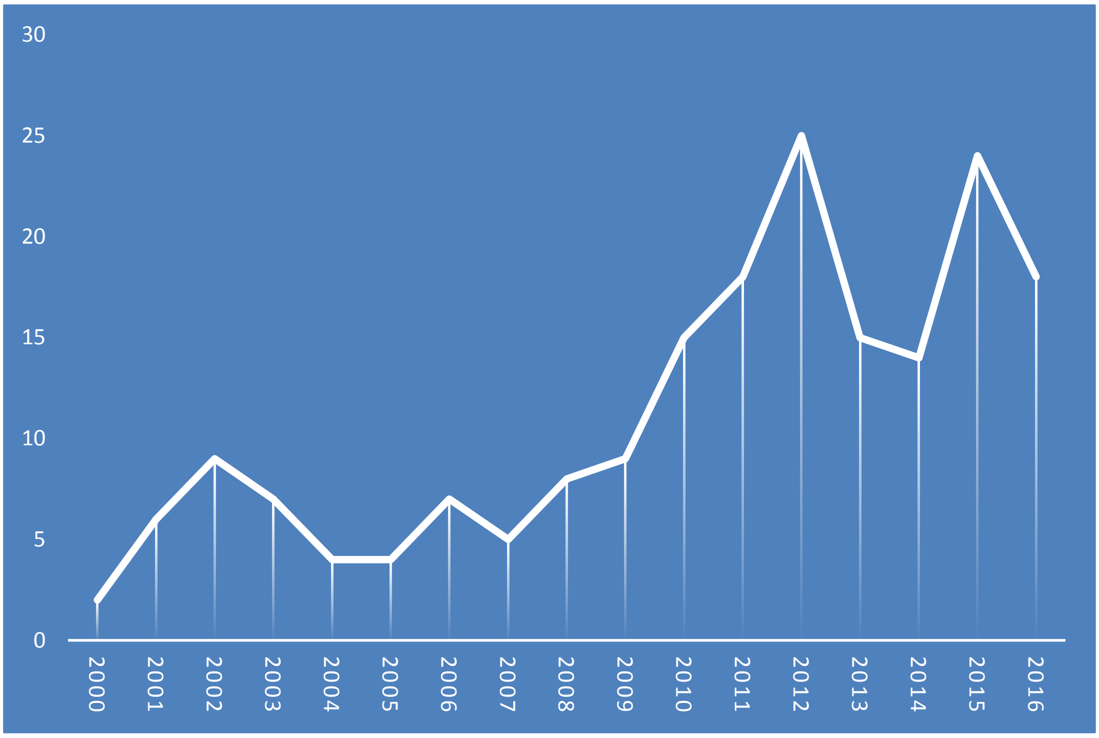


Figure 1: The number of peer-reviewed papers on "load-following nuclear" in Scopus. The topic has clearly drawn more interest in the past decade. Source: IASS auf Basis einer Scopus-Analyse, © 2017 Elsevier B. V.

This paper points out that:

- the technical capability of nuclear plants to ramp is generally assumed but rarely questioned and has never been demonstrated beyond around a third of a fleet's rated capacity;
- the economic impact of ramping on nuclear reactors is often omitted, and
- storage & curtailment (S&C), which drive up the cost of power supply, increases when baseload nuclear is combined with fluctuating wind and solar.

In other words, the "balanced mix" of nuclear, wind and solar will be the most expensive option – unless future nuclear reactors can ramp like current open-cycle gas turbines.

[3] The NEA lists German and French reactors as exceptionally flexible: "Although some French and German NPPs are flexible and operate in the load-following mode (see Figure 4.3 and NEA, 2011a), this is not a general case." See OECD 2012. Also see Batlle 2012: "According to EURELECTRIC (2010), properly designed or refurbished nuclear plants may perform in a rather flexible mode, but in most power systems (with e.g. the exceptions of France and Germany) nuclear plants are operated in a pure base-load mode, mainly based on security rather than economic reasons."

[4] Here, it is important to make a distinction between ancillary services (to support grid frequency) and proper load-following. The former are limited to a small percentage (generally 5% of less in the literature) of power output adjustment; such changes are indeed frequent in the German and French reactor fleets. Load-following is potentially much larger, so the question is what the maximum upward and downward ramp could be – and how often it could occur both per day and over a reactor's service life.

Contents

1. Quest for the best "deep decarbonization" path

1.1 The impact of ramping on nuclear

In the past few years, the best path towards "deep decarbonization" has become a hot topic in scientific literature. The goal is to design the best low-carbon power supply, with "low-carbon" assumed to be at least an 80% reduction and "best" generally being synonymous with "least expensive."

In a white paper, (Jenkins et al. 2017) reviewed 30 papers investigating deep decarbonization, some of which were themselves comparisons. Their review speaks repeatedly of nuclear as a "dispatchable low-carbon resource." It finds "strong agreement in the literature that a diversified mix" of low-carbon resources would be less challenging and less costly than relying "primarily (or even entirely) on the variable renewable energy resources such as wind and solar." Likewise, (Brick and Thernstrom 2016) speak of nuclear as a "low-carbon baseload resource."

Here, we see that nuclear is credited for being reliable ("dispatchable baseload"). Wind and solar are (correctly) identified as non-dispatchable, which is a drawback. On the other hand, these studies rarely if ever specify how dispatchable nuclear power would need to be at a given level of solar and/or wind power, much less investigate what the cost impact of this flexibility would be. In contrast, German researchers (Hirth et al. 2015) pointed out how lower capacity factors from ramping are often overlooked in international literature years ago:

> "The largest single factor {in total system cost} is reduced utilization of capital embodied in thermal plants, a cost component that has not been accounted for in most previous integration studies."

This frequent oversight in literature allows, on the one hand, supporters of 100% renewable energy schemes to claim that such power supplies will be easier than in reality; for instance, Stanford University's Mark Jacobson does not investigate hourly resolutions on the power market in his Solutions Project and therefore cannot map the pace or cost at which current infrastructure would need to be retired. On the other hand, thanks to this same oversight, supporters of nuclear power directly criticize Germany for combating climate change "with one hand tied behind their backs" without nuclear (Morton 2015). The contention is then taken up in journalism; in the Economist, it sounds like this (The Economist 2016): "Moreover, both solar and wind power are intermittent. That means they need to be paired with baseload generation."

Experts in Germany argued a decade ago that baseload is synonymous with inflexibility, which in turn is incompatible with fluctuating wind and solar power. The Germans coined the term *Systemkonflikt* (system conflict) for the incompatibility of nuclear with wind and solar. This German insight has entered the international debate quite strongly in the past few years as criticism of the need for baseload.[5]

[5] Most notably, the 2017 edition of REN21's Global Status Report contains a chapter on "Deconstructing baseload." The IPCC's phrasing "…high shares of variable RE [renewable energy] power…may not be ideally

1.2 Politics for nuclear to "back up" renewables in UK and US[6]

The lack of awareness about this inherent conflict also extends to policymakers. The British government has decided to build new nuclear reactors. One reason given in 2015 by then-Energy Secretary Amber Rudd was the "need to have an absolutely secure supply of electricity." She specifically explained that "nuclear provides the essential baseload that allows us to back renewables." (Carrington 2015) Though the Hinkley project remains uncertain, the policy support given to the proposed plant is impressive: state loan guarantees, floor prices indexed to inflation for power generated, and – curiously for this paper – a promise that any curtailed electricity from the two proposed reactors would be paid for in full.

Likewise, in April 2017 US Energy Secretary Rick Perry announced his intention to have a study done on whether baseload plants (which he defined as coal, nuclear, natural gas, and hydropower) are being made unprofitable, thereby leading to "the erosion of critical baseload resources." (Perry 2017) Though the investigation was widely understood as an effort to protect coal power – Perry himself complained about "regulatory burdens introduced by previous administrations that were designed to decrease coal-fired power generation" – the defense of baseload as indispensable is the same: "Baseload power is necessary to a well-functioning electric grid." (Roberts 2017b)

In the United States, however, energy policy is made less at the federal level than at the state level. The different state policy responses show the lack of consensus in the country on what role nuclear should play. Despite the diversity of stances, no US state's approach lines up with Germany's.

One early policy to promote baseload power is Mississippi's Baseload Act of 2008.[7] It essentially allowed Mississippi Power to pass on the cost of the Kemper CCS plant to ratepayers during the construction phase. Citizens in Mississippi, not the utility, thus assumed the risk of this plant because, as the Act put it, baseload "availability is essential to the orderly and effective operation of a reliable electric system… and to the public interest." Furthermore, "the State should take advantage of advances in nuclear, coal and other technologies… that facilitate the future reduction for minimization of regulated air in emissions." A similar arrangement was established in 2009 for the construction of the two new Vogtle nuclear reactors in Georgia, where the public, not the utility, covered all cost overruns. With the bankruptcy of Westinghouse, the status of those uncompleted reactors (as of late 2017) is unclear. Likewise, instead of being fired with synthetic gas made from local lignite, the Kemper CCS facility in Mississippi is now expected to run as a combined-cycle gas turbine without carbon capture and storage – though the capital cost is five times that of a conventional CCGT (Varro 2017 & Urbina 2017).

Those policies concern new builds. In 2016, concern about the economic viability even of existing baseload plants alarmed policymakers elsewhere. On 1 August 2016, the New York Public Service Commission (NYPSC) published plans to set aside 500,000 USD annually to prevent nuclear reactors from being closed. Essentially, the state established capacity payments for nuclear plants. The decision was part of its Clean Energy Standard, with a goal of 50% renewable power by 2030 (up from 27% in

complemented by nuclear, CCS..." has also been in the foreground of the debate between Jacobson and Clack (Jacobson 2017). Also see the chapters entitled "Looking Ahead: Traditional Baseload Likely to Disappear" and "Paying to Produce" in the 2014 edition of the Global Nuclear Industry Status Report, written by Germany-based researcher Raffaele Piria (Schneider 2014).

[6] Other English-speaking countries could be added to this list. For instance, Australian Prime Minister Malcolm Turnbull spoke of the need for "continuous power sources" when calling for new coal and gas plants instead of more renewables (the country does not have and is not planning nuclear). And as in other countries, there is a growing awareness among Australians of the inherent conflict between inflexible baseload and fluctuating renewables.

[7] http://billstatus.ls.state.ms.us/2008/pdf/history/SB/SB2793.xml

2014, with 23.5% percent being hydropower) and a 40% reduction in statewide greenhouse gas emissions by the same year. Nuclear needed special support towards that end because wholesale power prices were down.

The main reason for the low prices, however, was competition with relatively inexpensive natural gas in the power sector. Despite the rhetoric about wind and solar (potentially) offsetting nuclear generation, the share of fluctuating renewables in New York remains marginal. In 2015, the last year for which data was available in mid-2017, wind power made up only 2.9% of in-state generation; solar, 0.4%. Indeed, 2015 was the second best year for nuclear power generation in the state's history behind only 2013. These reactors are all old ones running at higher capacity factors; with one exception (from 1988), all were commissioned in the 1960s and 1970s.

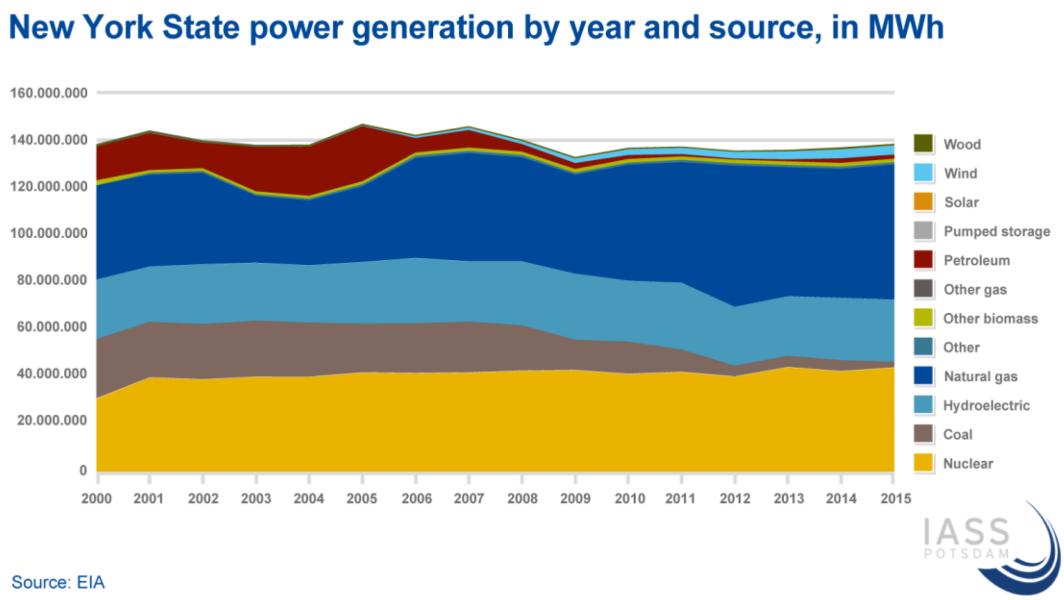


Figure 2: New York State power generation by year and source in MWh from 2000-2015. Nuclear power generation has actually grown in recent years, while wind and solar remain marginal. Source: IASS, based on data provided by the US Energy Information Administration (EIA).

Clearly, nuclear power plants were not being restricted in terms of the amount of power generated. Rather, wholesale prices (locational-based marginal prices or LBMPs) had fallen from around 40 USD per MWh in 2013 to 30-20 USD/MWh by 2015 (Hewitt 2016). The reactors were thus generating a lot of power, but at a loss. Bloomberg put the total generation costs of the US nuclear fleet at 35 USD/MWh on average in June 2017 (Polson 2017).[8] The DOE puts the average total cost of nuclear for the whole country at 34 USD/MWh (Table 3-3).

By the end of 2016, Illinois had also adopted subsidies for old nuclear. By the summer of 2017, Ohio, Connecticut, and New Jersey were reviewing such proposals. At the time, only 30 US states had nuclear power plants (EIA 2017), but the picture was not rosier for old reactors in the other 25 states not (yet) considering subsidies either. Rather, politicians elsewhere simply refused to subsidize old nuclear, most prominently in California.

The English-speaking world clearly has not made up its mind about the compatibility of nuclear with

[8] Note that continued operation when the electricity price is at least above the sum of fuel and operating costs reduces the burden of invested capital (sunk costs). The cost of fuel and operation seems to be close to zero: http://nuclear-economics.com/nuclear-power-short-run-marginal-cost/. A wholesale rate below the total cost therefore does not immediately lead to a shut down.

wind and solar. And for both journalists and policymakers who support nuclear, Germany specifically serves as an example not to follow – unfortunately, based on incorrect information.

1.3 Germany as a "bad example"

"Nuclear power is worth saving," wrote the editors at Bloomberg in April 2017, three years after the editorial board at the New York Times warned against closures of reactors in Illinois – and specifically pointed to Germany as a bad example to follow:

> "Only Germany succumbed to panic after the Fukushima disaster and began to phase out all nuclear power in favor of huge investments in renewable sources like wind and sun. One consequence has been at least a temporary increase in greenhouse emissions as Germany has been forced to fire up old coal- and gas-powered plants."

Here, two claims are made, both of them wrong. First, Germany did not fire up "old" coal and gas power plants; rather, German utilities were just opening up a new round of coal and gas generators with windfall profits from the first round of the EU's Emissions Trading Scheme, which started in 2005. New coal plants were built in particular to replace old ones not in compliance with upcoming requirements in the EU's Industrial Emissions Directive.

Second, Germany was hardly alone in its reaction to Fukushima in 2011 (Morris 2017):

- The **Swiss** Parliament reacted to public demonstrations in 2011 by resolving to phase out nuclear by 2034, though the details were unclear. The issue continued to be debated until 2017, when a referendum for a nuclear phaseout was successful.
- In June 2011, **Italy** also held a referendum on then-Minister-President Berlusconi's plans to construct new nuclear reactors. For the first time since 1995, enough people voted in the referendum to constitute a quorum, blocking Berlusconi's plans.
- In October 2011, **Belgium** reaffirmed its nuclear phaseout law from 2003, which specifies that the country's nuclear plants will be closed by 2025.
- In 2012, **Austria**, which blocked the opening of the country's only completed nuclear reactor in 1978, announced it would require labeling of power imports for retail consumers in 2015. The country's utilities responded to public sentiment by pledging that the share of nuclear power imports would be 0%.
- Finally, **French** President François Hollande ran for election in 2012 with a pledge first made in 2011 after the meltdown in Fukushima to reduce the share of nuclear from 75% to 50% by 2025 – a reduction even more ambitious than Germany's in terms of the number of reactors affected.

Chancellor Merkel's phaseout of 2011 looks less "panicked" if you remember that she was returning to a phaseout originally agreed a decade earlier – and only suspended six months before Fukushima. Nonetheless, in terms of climate change mitigation, the question of whether old reactors deserve subsidies thus partly comes down to how one answers the question: can renewables replace nuclear, or will natural gas – or even coal – be needed? The NYPSC wrote in its Clean Energy Standard, which set forth nuclear subsidies:

> "New York can look to another leader in renewable power—Germany—for a lesson in the unintended consequences of losing zero-emissions attributes from all its nuclear plants. Germany's abrupt closure of all {sic} its nuclear plants resulted in a large increase in the use of coal, causing total carbon emissions to rise despite an aggressive increase in solar generation."

Once again, two claims are inaccurate here. First, from 2011 to mid-2016 (when the NYPSC published its comment) Germany had closed nine reactors of 17, not all of them. Second, coal power fell between 2010 and 2016 by a rather insignificant 3 TWh (around 0.5% of total demand), as renewables grew nearly twice as fast as nuclear shrank (3). In fact, in 2015 and 2016 Germany had nearly as much non-hydro renewable power (almost 170 TWh) as it had ever gotten from nuclear, whose record year was 2001 at 171 TWh. Furthermore, Germany power exports have reached record levels since 2011; because renewable power has priority dispatch, foreign demand for German electricity primarily increases demand for coal power (Agora 2017).

Germany thus shows that coal is not needed to replace nuclear because renewables can grow quickly enough. By 2013, Germany had added more new renewable electricity than it had lost in nuclear in 2011. In three years, renewables had replaced electricity from half of the nuclear fleet, suggesting that the entire phaseout could theoretically be completed in six years with no need for additional power from fossil fuel.

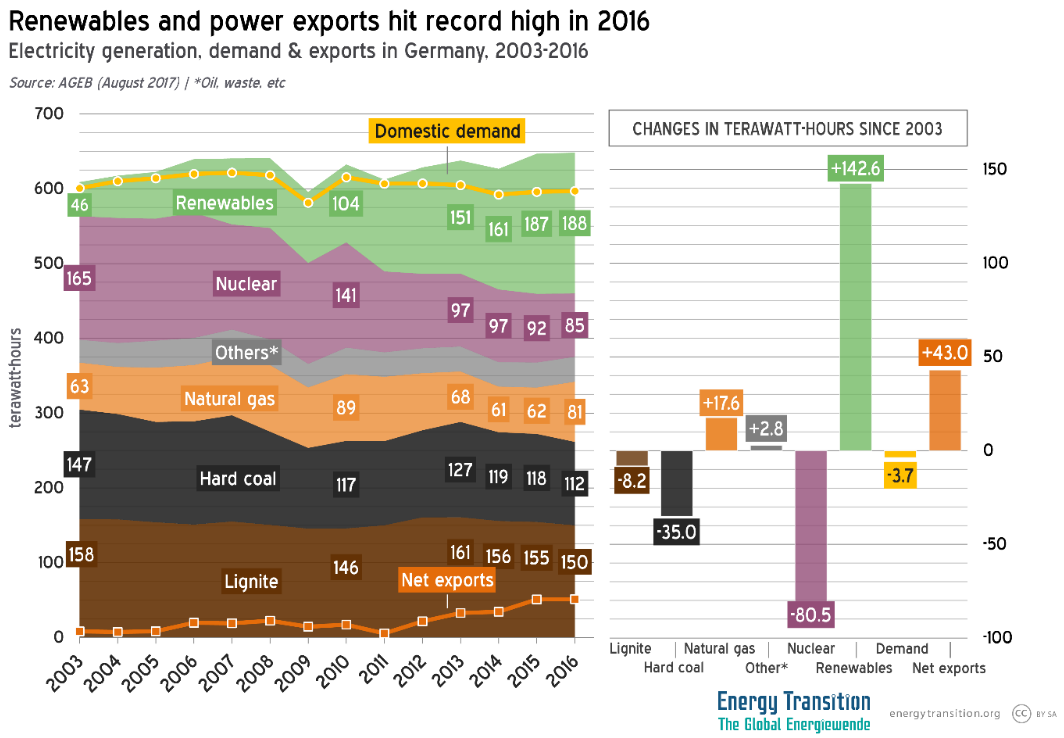


Figure 3: Renewable power production has more than compensated for the drop in nuclear power generation since 2010, the last year before the nuclear phaseout of 2011. In fact, nuclear was down by 80 TWh by 2016, while renewable power grew by 149 TWh during those years. Coal power generation has fallen slightly during that timeframe, mainly remaining stable because foreign demand for German power has reached record levels. Based on the merit order, hard coal has benefitted the most from foreign demand. Gas remains squeezed out, while lignite has not yet been offset much by renewables growth. 2003 was the year in which the first nuclear reactor was suit down because of the 2002 Nuclear Phaseout Act. Source: EnergyTransition.org, CC BY SA.

Nonetheless, the NYPSC decision drew some praise for proving, as one prominent journalist (now at the New York Times) put it, that "Nuclear power and renewables don't have to be enemies. New York just showed how." (Plumer 2016) In reality, New York's Public Services Commission had just shown that subsidies could be provided for old nuclear in addition to tax credits for wind and solar. The NYPSC had not by any means shown that nuclear is not an enemy of wind and solar in a balanced mix at high levels of wind and solar penetration. In fact, their compatibility had again not even been investigated, but merely assumed.

2. The German discussion in 2008-2010

2.1 Systemkonflikt versus “bridge technology”

The term “bridge technology” for nuclear power was probably first used in 1996 by the Commission of German Bishops (Vogt 1996). The idea was that renewables needed time to grow, and nuclear would give them the time needed. The label was intended to placate both camps in the debate: nuclear could stay on for now, but renewables would eventually push it out. Its coinage was not based on any scientific findings showing that nuclear would be a good – or perhaps even the best – bridge for renewables; rather, the term stemmed from a political desire to please everyone.

In 2002, Germany adopted its first nuclear phaseout under a coalition of Social Democrats and Greens. This coalition had reached an agreement with the owners of nuclear reactors in Germany. Each reactor was assumed to be able to produce a certain amount of electricity in a year based on its rated capacity and refueling schedules, and that amount was multiplied by 32 years to produce an allotment of electricity for each reactor. If a reactor produced less electricity for any reason (such as extended maintenance or ramping), it could theoretically run for more than 32 years, but it would have to close when its allotment of electricity had been generated.

In the run-up to the 2009 parliamentary elections, it seemed likely that a coalition of the two main parties that had not signed that agreement with the nuclear firms – the Christian Democrats and the Free Democrats – would be voted into office. Both parties indicated during the election campaign that they would back out of the agreement. Wind power had developed strongly during that decade, growing nearly fourfold from 10.5 TWh in 2000 to 39.7 TWh in 2007. That fast growth was in the foreground when the national debate on the future of nuclear began in 2008. Solar power production was far smaller at only 3.1 TWh in 2007, but Germany was adding new capacity on a massive scale during those years so that the figure reached 19.6 TWh by 2011.

From 2005-2009, Chancellor Angela Merkel’s first coalition still included the Social Democrats, signatories to the original nuclear phaseout. The environmental minister at the time was Sigmar Gabriel, who would have none of the talk about a nuclear future. On 1 July 2009, he spoke at the Atomic Forum, which was celebrating its 50th anniversary. In the presence of Chancellor Merkel, Gabriel said the organization had been “lying for half a century” on behalf of nuclear power (Biegert 2010).

Clearly, no extension to the nuclear plant commissions was possible with the SPD, and Gabriel explained exactly why to the press: “If the commissions are extended, no investor will commit billions of euros to offshore wind. You simply won’t be able to sell the power you generate to the grid.” He added, “For the four nuclear corporations, this election is do or die.”[9]

In the campaign for the 2009 elections, the role of nuclear in a power supply with a growing share of fluctuating wind and solar was discussed heavily in Germany. Nuclear proponents spoke of it as a

[9] It is worth noting that Gabriel specifically speaks of offshore wind, not solar or onshore wind. The expectations for this technology were greatly exaggerated at the time. See Jungjohann 2015.

"bridge technology" that would be necessary towards a low-carbon power supply while renewables continue to grow. Nuclear opponents argued that there was an inherent conflict (Systemkonflikt) between nuclear as inflexible baseload and, on the other hand, spiky wind and solar.

After winning the elections of September 2009 with a new coalition, the general expectation was that the nuclear sector would benefit; these firms' share prices rose. Chancellor Merkel stated that November: "During a transitional period, nuclear power will remain an indispensable part of our energy mix as a bridge technology until renewables are reliably able to replace it so that we don't have to import nuclear power from France and the Czech Republic."10

Immediately after the election results came in, there was talk about plans for a fundamental revamping of Germany's nuclear reactors. The new government had yet to complete its coalition agreement, but no one realistically expected new reactors. Günther Oettinger, then-Minister-President of Baden-Württemberg and later EU Energy Commissioner, held one of the more uncompromising pro-nuclear stances; he wanted to let the reactors run as long as possible. But Bavarian Environmental Minister Markus Söder warned, "The reactors should not be so fundamentally revamped that they are practically rebuilt." He called on his party to stick to the literal meaning of "bridge technology"; once renewables had grown enough, nuclear would go (Spiegel 2009). In the fall of 2010, the decision finally became law to allow the reactors to remain in operation for an additional 8 to 14 years, depending on the reactor. The new Environmental Minister Norbert Röttgen made it clear that the extensions were not a "phaseout of the nuclear phaseout," as critics charged: "Nuclear power can only be used over the long run if a majority of people accept it," which was then not the case – "and I don't think that will change." (Käfer 2009)

Critics of baseload did not deny that wind and solar require backup but specifically argued that inflexible plants were unsuitable for the task; they criticized both coal and nuclear in that respect. Rainer Baake, currently Energiewende Undersecretary and then-head of German environmental organization DUH in 2009, stated: "Sticking with inflexible central coal or nuclear power stations is increasingly hampering the growth of renewables that citizens desire." (Odenwald 2009) Utilities that did not own nuclear assets agreed; in the same article, one CEO said, "Nuclear is completely unsuitable as a bridge technology."

A slew of studies investigating the issue were published. In April 2009, the Environmental Ministry – still under Gabriel's leadership – published a position paper entitled, "Nuclear power as an obstacle." (BMUB 2009). It argued: "A power supply based largely on renewables does not need baseload power plants," but flexible backup capacity (specifically, combined-cycle gas turbines, even though open-cycle turbines ramp the best). It depicted nuclear reactors as "the least flexible facilities in the traditional power plant fleet." It reminded readers that low overnight retail rates had been offered for decades in order to incentivize electric heating specifically so that baseload power plants would not have to ramp down on a daily basis overnight. And it explicitly worried that nuclear power was not a bridge at all, but rather a blockade; the growth of renewables would be slowed down and renewable power curtailed to keep nuclear reactors from having to ramp. In 2008, the first negative prices had been posted on the wholesale market when inflexible baseload plants had failed to accommodate a surge in wind power production. The Environmental Ministry pointed out that 8 GW of nuclear capacity was off-line at the time for maintenance, but still around 13 GW of nuclear "could not be ramped down quickly enough" to prevent negative prices. It concluded that the nuclear phaseout was an opportunity, without which "it will be very difficult to increase the share of renewables to at least 30% by 2020 and 50% by 2030."

[10] This concern about nuclear power imports from France and the Czech Republic also turned out to be exaggerated; reactors in those countries have not increased their already high output to serve any German demand, and neither country has added any reactors since 2009.

The German Advisory Council on the Environment (SRU) followed up with another study in May 2009 comparing four options (SRU 2009):

1) a fast renewal of the existing fleet, including coal, without CCS;

2) a renewal with CCS added after 2020;

3) nuclear commission extensions and new builds; and

4) expansion of renewable energy.

It found that:

- new baseload coal plants being built would endanger carbon emissions even beyond 2050 (because they can run for more than 40 years);
- 100% renewable electricity is possible and preferable to other options;
- and a large fleet of baseload power plants is incompatible with further renewable energy growth.

To promote comprehension among a wider audience, the study included a glossary and a chart showing what became known as the “residual load” (power demand minus renewable power generation), which conventional plants would have to cover.[11]

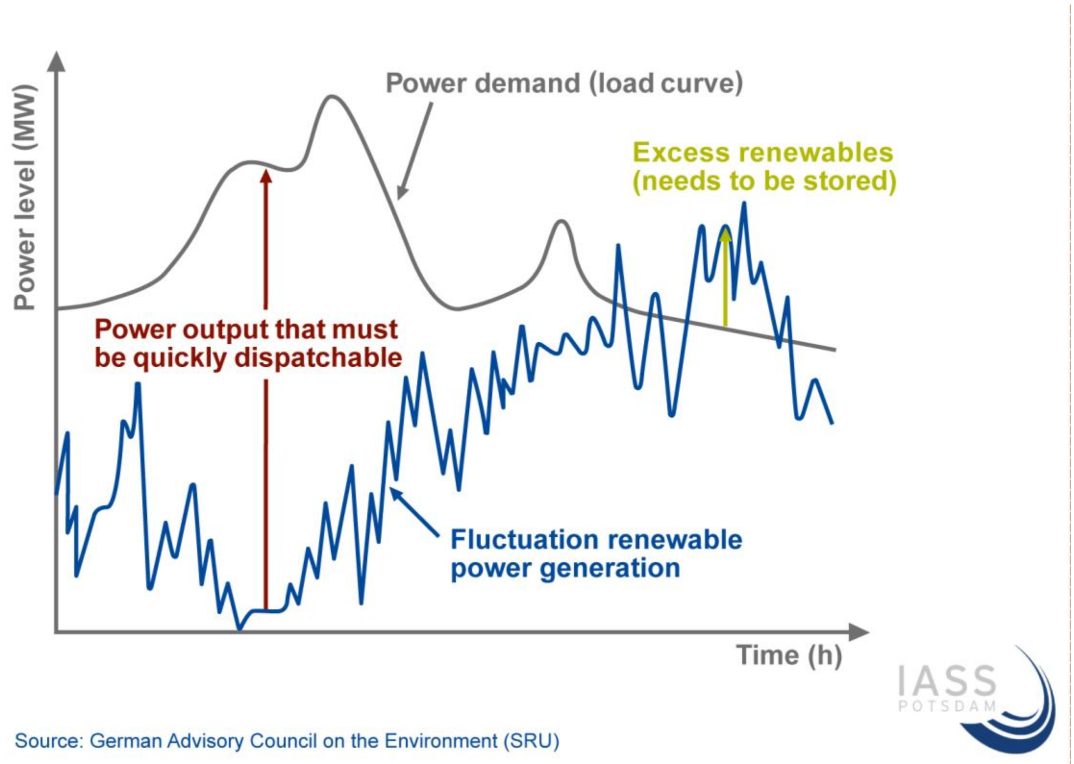


Figure 4: The chart from 2009 showing how fluctuating wind and solar is incompatible with baseload. Based on the SRU’s study. Source: IASS based on a study by the German Advisory Council on the Environment (SRU).

[11] The SRU followed up with a 390-page special report (PDF) in January 2011 that added detail for experts.

In December 2009, researchers from Fraunhofer produced simulations of what the German power sector could look like by 2020 with 47% renewable electricity (BEE 2009). This scenario came from German renewables organization BEE and was far more ambitious than the official target of 30% renewable power adopted earlier that year. The share of fluctuating wind and solar alone was above 30% in the BEE scenario.

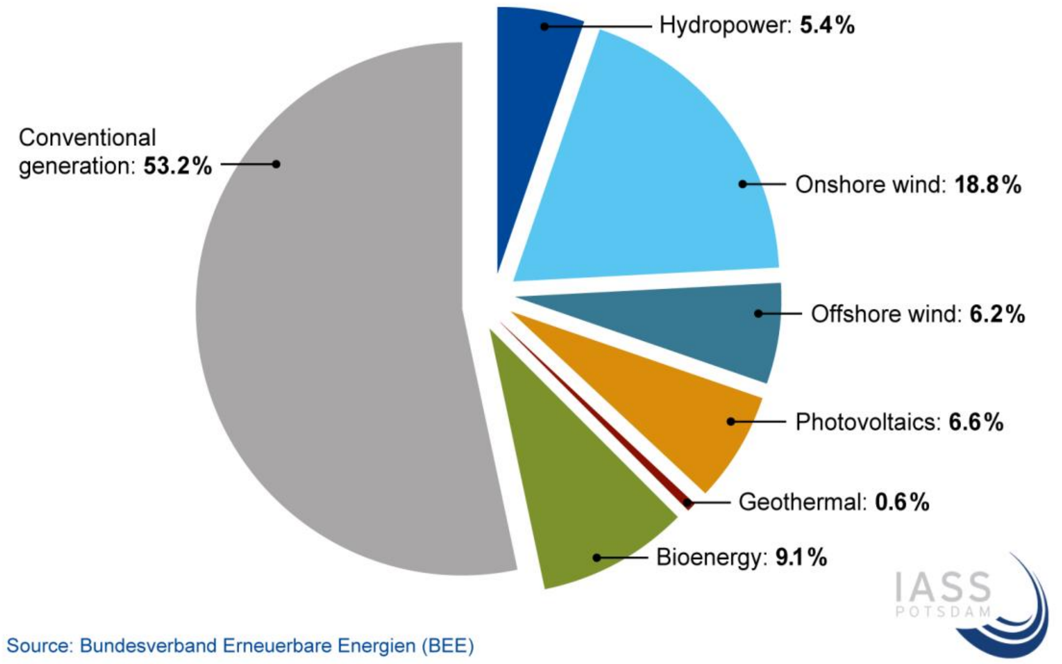


Figure 5: The BEE's breakdown of power sources by 2020 in its scenario from 2009. Source: IASS based on data provided by the Bundesverband Erneuerbare Energien (BEE).

The BEE's visualization (Figure 4) clearly showed wild fluctuations in the residual load. It did not look anything like baseload. What's more, it sometimes went negative, was very frequently below 25 GW (the must-run level of Germany's conventional fleet at the time), and often had extremely steep ramps.

In trying to state its findings clearly, the study struggled with their newness. "Today (2007), around 40 GW of power plant capacity can run all the time year-round. But in this scenario {with 30% fluctuating renewables}, that will no longer be the case by 2020: by then, all conventional generators will need to switch off for 84 hours a year – in other words, there will no longer be any 'classic baseload', so to speak."[12] Note that 30% wind and solar is roughly what France will have if it replaces 25% of its nuclear supply with fluctuating renewables; we come back to this issue below.

In 2010, the BEE produced its own idealized version, clearly showing that the residual load would completely disappear over the course of a week – only to come roaring back a day or so later. Whatever backed up renewables would need to disappear from the grid entirely for hours at a time, then remain online at a very low level for additional hours, and then ramp up significantly (Renews 2010).

[12] The study stresses that the simulation assumed the smallest conventional unit would have 500 MW, which is not the case, but the assumption at least underscores what the impact would be on all generation facilities of significant sites. Furthermore, this particular finding assumes no "balancing measures" (storage, international power trading, etc.).

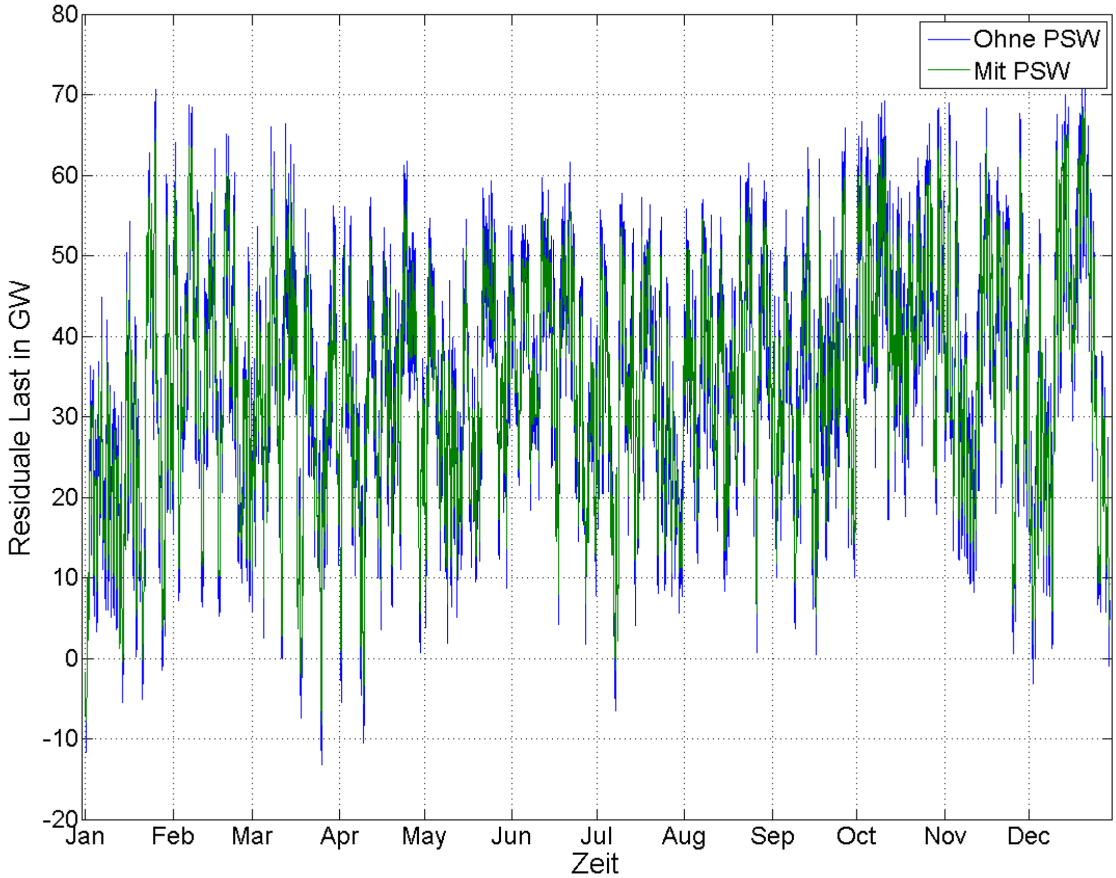


Figure 6: The residual load in the BEE scenario with (green line) and without (blue line) pumped storage. Copyright: Bundesverband Erneuerbare Energien (BEE).

Entitled in German "Renewables and baseload power plants – a system conflict?" the BEE paper quoted a passage in English from the Guardian from talks held between EDF, EON, and the British government. A Google search for this passage reveals numerous citations from German websites but none at all from English-speaking countries, including from the Guardian. The publication in the UK apparently led to a discussion in Germany, not in the English-speaking world.[13] The full statement[14] is a frank admission of the incompatibility with wind and nuclear (solar not yet having been perceived as a threat):

> "As the amount of wind capacity increases, there will be occasions, when wind output is high, when the output from low marginal cost plant, primarily wind, other renewables and nuclear, will exceed electricity demand and as a result either nuclear or wind plant will need to be curtailed…. Constraining low marginal cost, low carbon generation results in underutilised zero carbon generating capacity, and damages the economics of these projects, meaning that less will get built….

[13] The original EDF paper presented to the British government is still available online.

[14] EDF writes: "SKM's analysis does not consider the implications of a greater amount of new zero carbon generation (typically new nuclear, fossil fuel with CCS and non intermittent renewables) coming on to the system." In case of curtailment, "Wind generators will be in receipt of a financial subsidy, and therefore will still want to generate at negative power prices in order to receive the subsidy." Later, the proposed new reactor at Hinkley received such support: the strike price is to be paid for all electricity that could be generated, not only the amount actually produced.

… we see greater problems in the period around and beyond 2020, and at any time that generation other than wind needs to be curtailed…. Our detailed analysis shows that, as the intermittent renewable capacity approaches the Government's 32% proposed target, if wind is not to be constrained (in order to meet the renewable target), it would be necessary to attempt to constrain nuclear power more than is practicable - even when assuming that all other non wind plant has already been constrained first. This leaves only one option available - once constrained, nuclear will need to remain constrained off for longer periods of time."

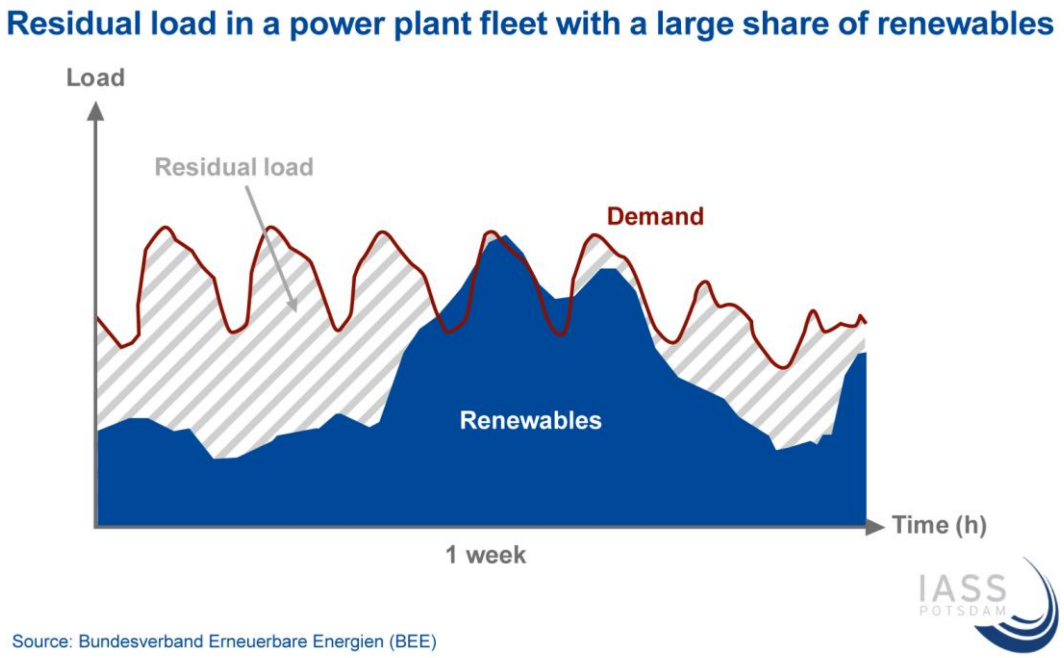


Figure 7: The BEE's simplified version of Figure 4 above. The disappearance of the residual load for much of a 24-hour period is clear to see. Whatever covers that residual load without have to ramp quickly and be able to switch on and off for just a few hours. Source: IASS based on data provided by the Bundesverband Erneuerbare Energien (BEE).

One reason why EDF's analysis became part of the public debate in Germany, but not in the UK may be that no British civil society actors came up with simplified versions of complex graphics the way Germany's BEE did. It is harder to see the conflict in EDF's two charts below than in the ones produced in Germany at the time.

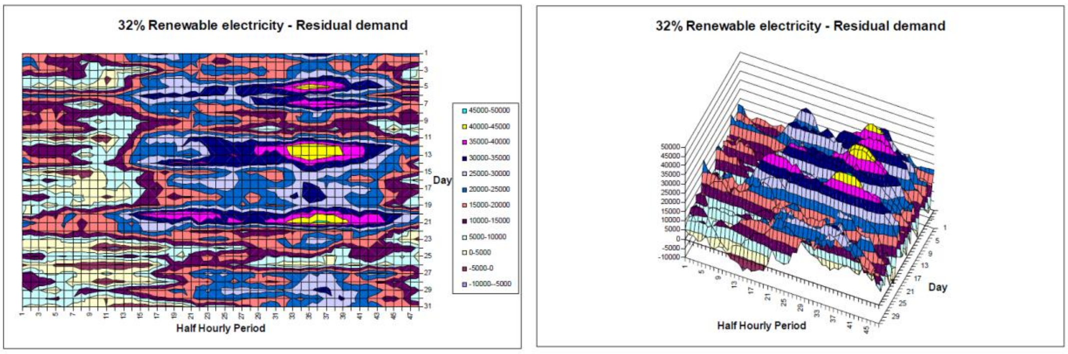


Figure 8: EDF's charts showing the same basic conflict between fluctuating wind and solar as in Figure 4, though the conflict is harder to see. The 3D rendition on the right is clearer but perhaps still too complex for civil society actors hoping to engage with the public. Source: Electricité de France. Public domain, study from 2008.

2.2 The nuclear sector reacts, highlighting flexibility

The list of studies above challenging the notion of nuclear as a bridge technology is not exhaustive. Indeed, the CDU's Economics Council spoke of an "inflationary" slew of such studies serving a specific "clientele"[15] – meaning proponents of renewables. But numerous studies were also published in favor of nuclear as well.

In 2010, RWE's CEO claimed that "nuclear power and renewables are partners, not enemies." (Vorholz 2010) Representatives of RWE and EON gave joint presentations demonstrating, as one slide show from September 2011 shows, the flexibility of 10 reactors operated by the two firms.[16]

Also in 2010, a special issue of the International Journal for Nuclear Power was published on the load-following capability of nuclear reactors (Ludwig 2010). Like the representatives of RWE and EON, the Journal argued that German reactors had been designed to follow loads originally; they had not been revamped for this purpose. Still overlooking solar, the authors write: "Operating experience clearly confirms that the existing reactors are well-suited to compensating for load fluctuations like those that will result from a considerable growth of wind power."

One concern was that load-following would endanger reactor safety, but the authors reject the idea: "Because German reactors have largely run at constant output up to now, there are considerable reserves in terms of material fatigue."

Specific flexibility varies from one reactor design to another. The European Utility Requirements specify for the EU that new Gen3+ reactors (none of which have been completed) must be able to ramp from 100% to 50% of nominal output and back up to 100% regularly (100-50-100) for 90% of a fuel cycle. These requirements are not, however, a significant improvement over the levels reported for Germany's existing fleet and are less than what is reported for the latest French reactors.

For Germany, the Journal states that around 10 GW of ramping was possible at the time, nearly half of the roughly 21 GW online. Specifically, boiled-water reactors (BWRs) were held to be able to ramp by 60%; pressurized water reactors (PWRs), by 50%. When the control rods are optimized, power

[15] The specific document is no longer available online but was mentioned by the media in February 2011, the month before Fukushima.

[16] The two authors also published an essay on load-following in issue 5, 2012, of the International Journal for Nuclear Power, but the point was politically moot by that time.

output can even be reduced to 20% in PWRs. Many French reactors (reportedly 40 of 58, see Schneider 2009) have been modified in this way; the Journal states that they can ramp down to 30% of rated output.

The Journal writes that German BWRs can ramp from 100-40-100 percent 12,000 times over their service life – equivalent to once per day for 32.8 years. Like other studies, the Journal also points out that power reductions are relatively easy; the challenge is ramping back up. While nuclear reactors often need a day or two to reach full capacity after a shutdown, only an hour or two are needed if the system remains hot.

The authors based this information partly on a previous study conducted by the IER (an energy research institute at the University of Stuttgart) in October 2009 (Schneider 2009). It investigates two scenarios: one with the original nuclear phaseout (which would have closed the last reactor in the early 2020s) and the other with the extension to the mid-2030s. It finds that there is no technical reason to view nuclear reactors as hampering the growth of renewables; on the contrary, from both the economic and climate perspective, the study argues that the phaseout would be "counterproductive."

Like all other studies from those years, the IER underestimated the growth of photovoltaics dramatically, expecting only 14.66 GW by 2020 (the country had more than 41 GW in 2017). Otherwise, the expectations for onshore wind fell short (an expected 36.83 GW by 2020, compared to an actual 46 GW at the end of 2016), whereas expectations were exaggerated for offshore wind (more than 10 GW by 2020, compared to the current target of 6.5 GW). Again, these deviations are typical of assumptions from those years (Jungjohann 2014).

In agreement with the aforementioned studies endorsing renewables, the IER's pro-nuclear study finds that ramping will become so commonplace by 2030 (at 40% renewable electricity)[17] that "there will no longer be a clear distinction between baseload, medium-load, and peaking power plants." The authors agree with nuclear critics that "gas turbines… are especially suited to covering load fluctuations." Oddly, the report shies away from a direct comparison with nuclear; Table 4.2 in the study shows the ramping abilities of OCGT, CCGT, lignite power plants, and hard coal power plants – but not nuclear. One reason may be the slightly different ramping capabilities of the German nuclear fleet (but then, a useful distinction is made between gas turbine types). The authors write that the Convoy and the Pre-Convoy reactors (the last six built in Germany) can ramp from 100-20-100, whereas older BWRs can ramp from 100-40-100.

Under these conditions, the IER has the German nuclear fleet being able to ramp down from 20.5 GW to somewhere below 10 GW. No specific lower number is ever stated; we can simply see from bar charts that the nuclear fleet can drop below 10 GW. Otherwise, detailed information is given for the scenario with extended reactor commissions: for instance, the maximum excess amount of power that needs to be stored or curtailed is 15.7 GW with 37.8 GW of wind power and 11.5 GW of solar power simultaneously being generated. The lack of specifics about the must-run level is a strange omission in an otherwise detailed 82-page study purporting to highlight the flexibility of nuclear reactors.

2.3 Discontinued TAB study

Perhaps the most interesting German study from this era was never completed. It is unique in that the

[17] The official goal in the Renewable Energy Act of 2009 (published in 2008) was 30% green power by 2020. The 40% by 2030 was thus an assumption. Germany had around 42% green power as a share of demand in the first half of 2017; see Morris 2017.

organization behind it had no horse in the race: neither renewables nor nuclear.[18]

After the elections of 2009, the Office of Technology Assessment at the German Bundestag (TAB) began investigating the compatibility of nuclear power with fluctuating wind and solar. In addition to reviewing data, TAB held workshops and collected opinions from various camps. This input would have been very helpful in a debate where reliable information about the flexibility of nuclear is hard to come by. It would have been interesting to know whether other experts from the nuclear sector were as eager as those from RWE and Eon (cited above) to ramp their reactors – or whether they were as reluctant as EDF was in its aforementioned comments from the UK.

In late 2009, Germany was about to embark on an unprecedented experiment: adding wind and solar at levels not previously seen on a grid that still had around 30% nuclear power. If anyone was able to prove that nuclear is compatible with wind and solar, Germany was. But in March 2011, Chancellor Merkel's revocation of reactor commission extensions put an end to this experiment.

TAB's investigation was therefore discontinued. Workshops scheduled for March and April 2011 were canceled, and no paper was ever published. But in 2017, TAB released a 120-page review of the discontinued project in light of renewed international interest in the topic. The study is available in English, but the present paper is based on the German version (Grünwald 2017).

The TAB report confirms the must-run levels described above (between 20 and 50% for PWR and 60% for BWR) but adds that "talks with power plant operators revealed that these levels are not yet reached on a regular basis."

The study investigates three strategies for German reactors in its scenarios:

- Limited flexibility (100-50-100 for PWR and 100-60-100 for BWR),
- Flex20 (100-20-100 for PWR and 100-40-100 for BWR), and
- Flex0 (a complete shutdown for at least three hours, with at least one hour of full operation).

The study speaks theoretically of the need for "complete flexibility… beyond what has been seen in practice." The "limited flexibility" mode was, however, the only one for which practical experience was (and is) available. "If nuclear and renewables are to work together without conflict, nuclear reactors would need to be operated more flexibly," the authors write. The Flex20 mode is described in some German reactor operating manuals (though it can be observed in a small number of French reactors to a limited extent as shown below), whereas Flex0 is based on an emergency shutdown procedure described in the manuals. It is not intended for regular use in load-following; the study wanted to investigate both what it would look like in practice and find out whether reactor operators believed it would be feasible on a regular basis in practice.

These three operation modes were then investigated in three scenarios for 2030: a 20-year reactor commission extension, a 12-year extension, and a nuclear phaseout. It was assumed, in line with the most recent Leitstudie,[19] that Germany would have 65% renewable power in 2030. Just over three quarters of that amount would be wind and solar, which would therefore make up roughly half of German power supply. Note that this share is more ambitious than Germany's official current plan, which would only reach 65% renewable electricity in 2040. As the table below shows, the estimates

[18] TAB shares this independent stance with the Bulletin of the Atomic Scientists.

[19] The *Leitstudie* was a regularly updated collection of scenarios for the Energiewende. It was the closest thing Germany had to a master plan for its energy transition. Since 2011, there have been multiple studies investigating various aspects.

for Desertec (largely concentrated solar power or CSP) and offshore wind were – as in the assumptions used by the IER – exaggerated, while PV and onshore wind were underestimated.

In the study, the amount of electricity curtailed was still modest in 2020 at 2.5 TWh (around 0.5% of total power generation), most of which was the result of congestion on the grid, not the inflexibility of the power plant fleet. But by 2030 the figures looked much different.

Table 1: The TWh expected by 2030 in the Energy Concept and Leitstudie along with the actual numbers from 2016. Large systems (especially offshore wind and CSP from Africa) were overestimated, while onshore wind and PV (more distributed systems) were underestimated. Source: IASS. Data from Leitstudie 2010 except data for 2016 from AGEB (Arbeitsgemeinschaft Energiebilanzen).

	Energy Concept (2030)	Leitstudie (2030)	Actual 2016
Wind onshore	73	87	66.3
Wind offshore	48	95	12.3
PV	36	55.2	38.1
Biomass	46.2	56.1	44.9
Hydro	25.1	24.5	20.5
Geothermal	3	6.6	(under “other”)
CSP (Desertec)	18	15	0

The percentage of renewable power curtailed in 2030 was 3.6% with a phaseout, 6.3% with 12-year extension, and 8.3% with 20-year extension (assuming limited flexibility). Assuming a 12-year extension of reactor service lives in the “limited flexibility” mode, each reactor would have to go through some 300 to 400 cycles of 100-60-100 in 2030 alone. As of 2010, they had undergone some 2,000 such cycles on average out of the 15,000 considered possible. Theoretically, plenty of reserve flexibility was left; 15,000 cycles is enough for 41 years of daily cycling.

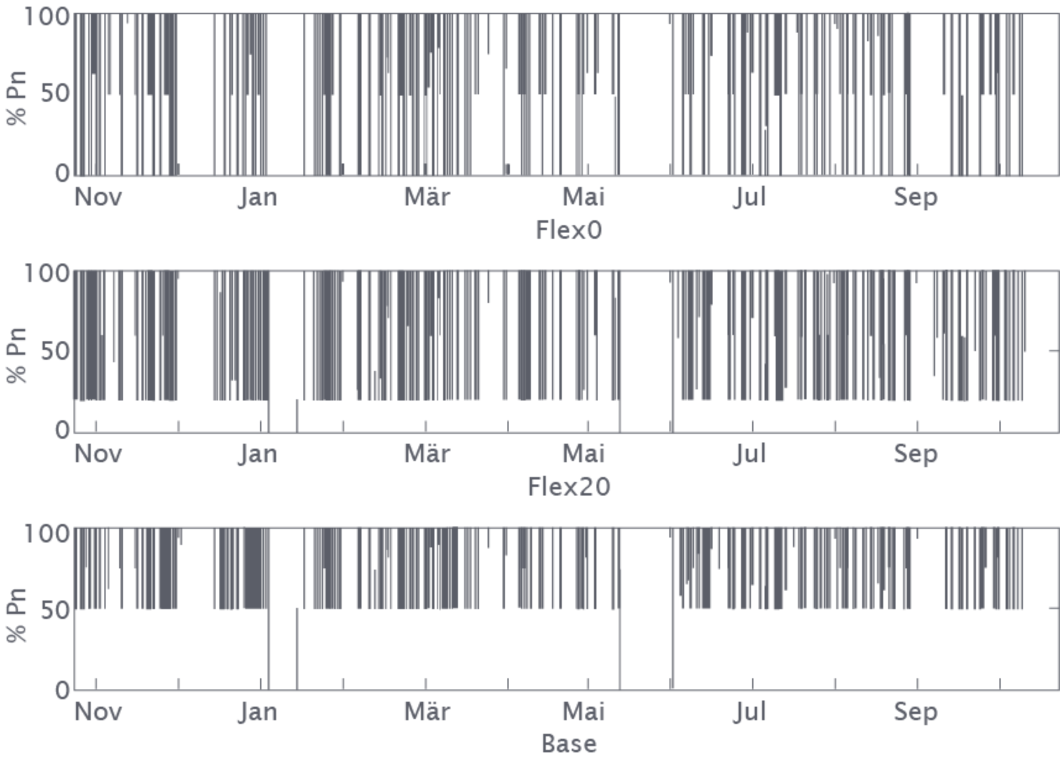


Figure 9: Modelled operation of the Philippsburg 2 reactor in 2030 if plant commissions are extended for 12 years under various operating mode assumptions. The dark areas represent reductions in the power generation (ramping); the white areas, power generation. At the bottom, we see the category of "limited flexibility" – the maximum ramping shown by individual German reactors in practice at around 50%; note, however, that the German fleet as a whole has never ramped by more than around a third. In the middle, we see the maximum ramping already attained by individual French reactors at 75%. At the top, we see complete shutdowns – 100% ramping – only exhibited in emergency shutdowns. These emergency shutdowns constitute the study's "highly flexible load-following mode of operation" that would make nuclear reactors compatible with wind and solar. Copyright: Technikabschätzungsbüro und Ecofys 2011.

If the Flex0 operating mode (currently only used for emergencies) is possible, each reactor would ramp around 100 times a year on average. This number does not, however, indicate that each cycle went from 100-0-100; instead, all load-following events are counted, with 100-0-100 being a possibility. Because this operating mode provides greater flexibility than coal plants can, the amount of power curtailed in 2030 would be lower in this case if more reactors are online.

The study concludes that "in principle, nuclear reactors operating in a highly flexible load-following mode of operation are compatible with the renewable energy targets from a technical perspective." The problem, of course, is that no "highly flexible" nuclear reactors exist; the ones currently in operation fall within TAB's category of "limited flexibility," which leads to higher curtailment.

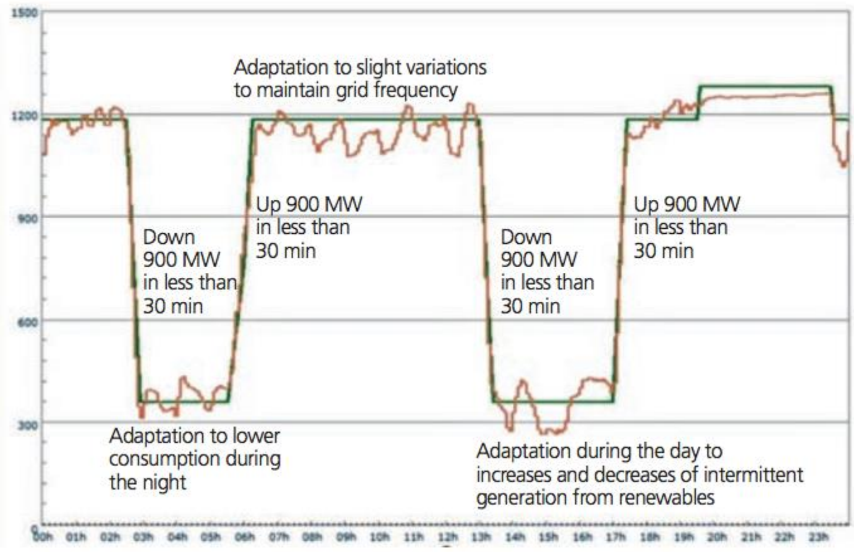
3. Nuclear (in)flexibility in practice

3.1 Demonstrated fleet flexibility in France and Germany

The need for flexibility concerns an entire fleet. If an individual reactor ramps significantly so that the others don’t have to move at all, this behavior may be an indication that nuclear reactors ramp differently than coal and gas turbines do. What matters is not only the extent to which a reactor ramps but also how often it has to. What happens in the entire French fleet during those instances when an individual French reactor ramps significantly? The data show that, rather than all reactors ramping by, say, a mere 7%, one out of ten ramps by 70% so that another nine continue generating power at an unchanged level. In a brochure prepared for COP21, EDF uses the following instance from 13 September 2015:

INTERESTING FACTS

THE POWER GENERATED BY ONE OF THE REACTORS (1,300 MW) AT THE GOLFECH NUCLEAR PLANT OVER A 24-HOUR PERIOD, ONE DAY IN SEPTEMBER 2015, IN RESPONSE TO VARIATIONS IN ELECTRICITY CONSUMPTION AND GENERATION FROM INTERMITTENT RENEWABLES:



In the latter case, it must be possible to rapidly reduce generation when wind and solar begin to generate their “unavoidable” energy or, conversely, rapidly start up generation when solar or wind production drops. These adjustments are especially important when intermittent generation from renewables is substantial.

Figure 10: A chart from an EDF brochure showing the flexibility of a single reactor. Copyright: Electricité de France.

The reactor in question is Golfech 1.[20] EDF claims that this plant ramped down and up again by 75% (100-25-100) twice that day, the second time to accommodate "increases and decreases of intermittent generation from renewables." However, the fluctuation in the production of wind and solar power across the country during those hours was smaller than the adjustment at this single reactor: wind and solar made up 3.9 GW at 1 PM, rising to 4.4 GW at 3 PM before falling to 3.6 GW at 5 PM. The reactor thus moved by 900 MW allegedly to accommodate a 500 MW increase in wind and solar followed by an 800 MW decrease. Overall, France's nuclear fleet barely changed its production that day, as can be seen from the chart below.

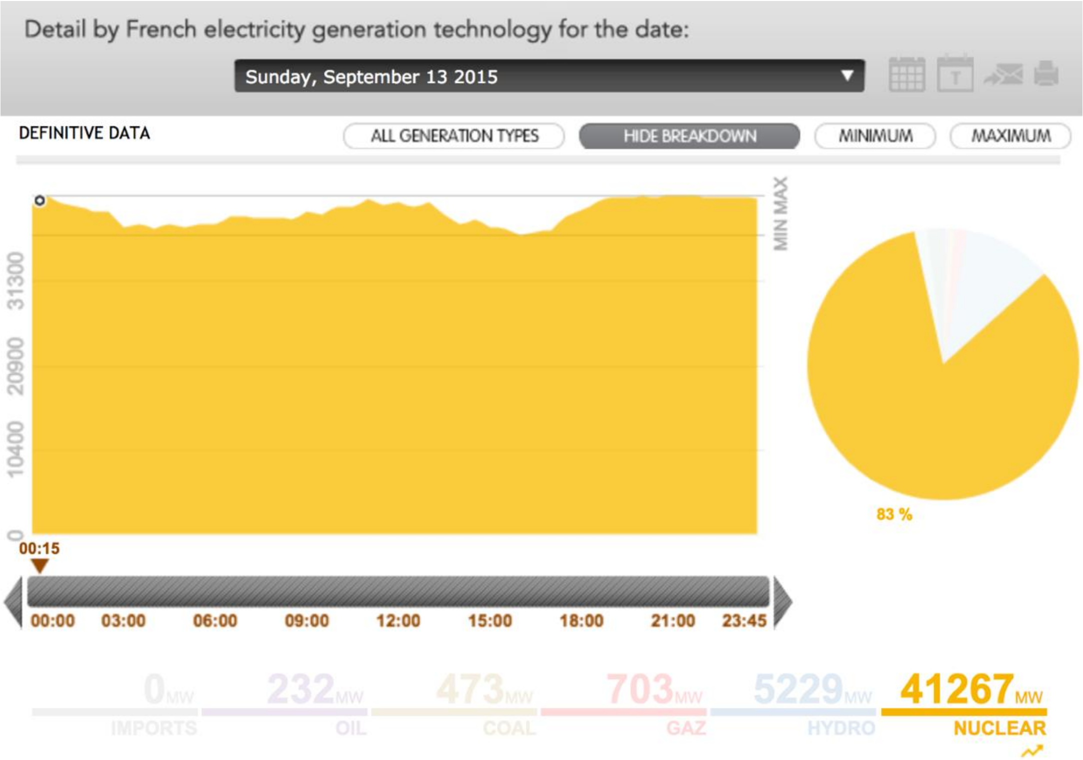


Figure 11: Nuclear power production on the day when the reactor shown in Figure 10 ramped greatly. The fleet as a whole adjusted its output only by around 10%. Copyright: RTE éco2mix.

A look at the data by generation unit reveals (Figure 12) that five reactors adjusted their output, each quite dramatically, on that day (with one replacing another during the course of the day). If 40 of France's 58 reactors are indeed capable of following load, they obviously take turns. They do not all adjust output slightly; rather, as few of them as possible adjust output as much as possible so that as many reactors as possible do not have to change output at all. This behavior is particular to nuclear; no fleet of coal or gas turbines exhibits such behavior.[21] The implications of this unique behavior require further study: might a small fleet ramp poorly if the flexibility cannot be spread out well? Might losing a lot of power at specific points (rather than a little power everywhere) be a challenge for grid operators?

[20] Neither the calendar day nor the reactor are clearly indicated in the EDF publication but can be identified from the raw data.

[21] All reactors in France belong to EDF. Sacrificing one plant does not benefit a competitor. This ownership issue requires further study.

On the other hand, 13 September 2015 was not a date on which the French fleet showed its full flexibility, with adjustments only coming in at a tenth of output. The fleet has ramped by a third at least once. In a paper investigating France's plans to reduce the share of nuclear from 75% to 50% by 2025 (first adopted in 2012), researcher David Buchan lists 28 October 2013 as a day on which "nuclear shows flexibility." The fleet's performance here is indeed more impressive, with 13 reactors ramping significantly. Nonetheless, the unique behavior of individual reactors sacrificed to keep others unchanged is clear to see.[22]

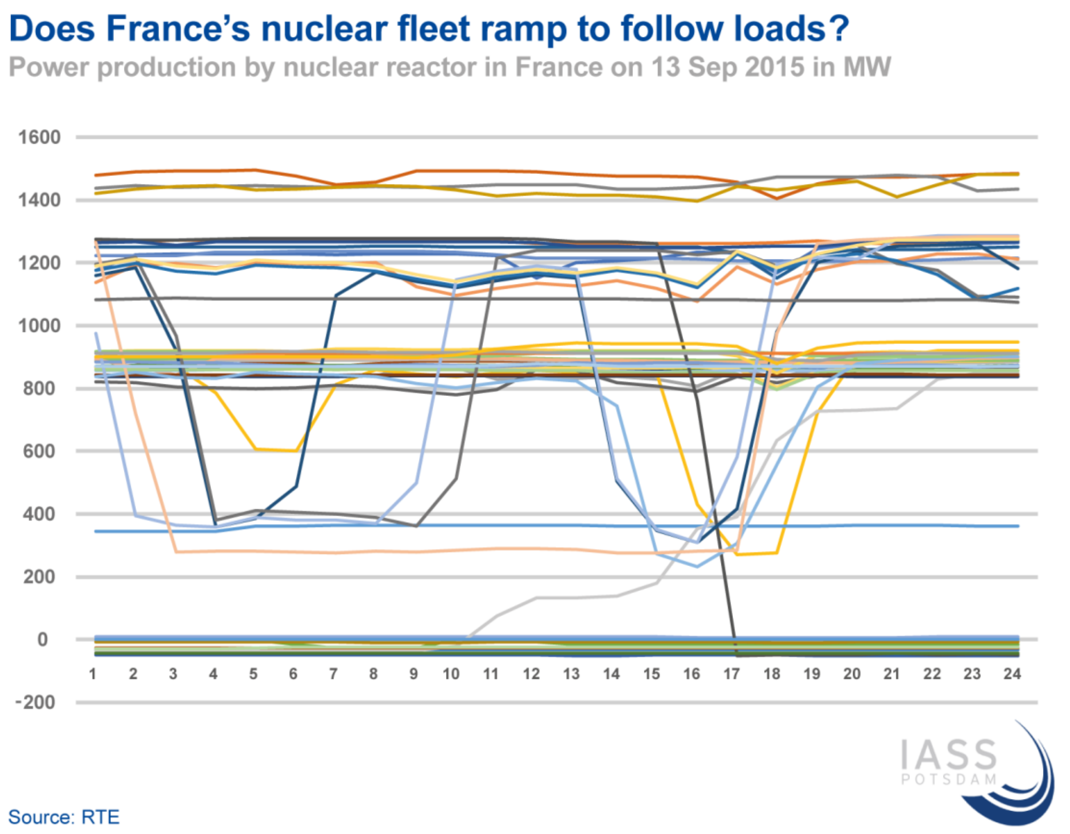


Figure 12: Unit-wise power production by the hour on 13 Sep 2015 for the entire nuclear fleet in France. Most reactors ramped so little that their rated capacities are clear to see: around 900 MW, 1200 MW, and 1400 MW. At the bottom, we see reactors consuming power during downtime. Data from Réseau de Transport d'Électricité 2016.

There is a great reduction in nuclear power generation just after midnight (from around 37.7 GW at midnight to 31.7 at 4 AM), but the upward ramp is even more impressive: back up to 45.7 GW at 9 AM – an increase of around 50% counted from the low level or a third from the high level (remember: ramping up is considered harder than ramping down). Buchan explains that a storm came through during that night, at a time of already low demand, thereby keeping wind power high at nearly 6 GW, roughly the amount that nuclear ramped down. However, wind power production did not fluctuate during these hours; demand dropped. When demand picked up again, both nuclear and hydropower (which roughly doubled its output from 4 AM to 12 noon) ramped up.

[22] To complicate matters further, a JRC report from 2010 states that the largest category of French reactors does not ramp to stabilize the grid: "In fact in France 1500 MW reactors are not operated in secondary regulation and as a matter of fact the maximal secondary reserve is by 65 MW." That would explain Figure 12 above, but Figure 13 below shows major ramping at one such unit.

The German nuclear fleet display the same behavior of sacrificing one reactor to keep others unchanged. The fleet also does not seem to have ever ramped by more than around a third either. One such instance occurred around Christmas of 2016, when the fleet dropped from just above 7 GW to below 5 GW before rising back up again (with five reactors) to around 6.5 GW, an increase of around a third. Note here that one reactor (Emsland A) cuts off entirely during this process for refueling and does not come back on during this timeframe.

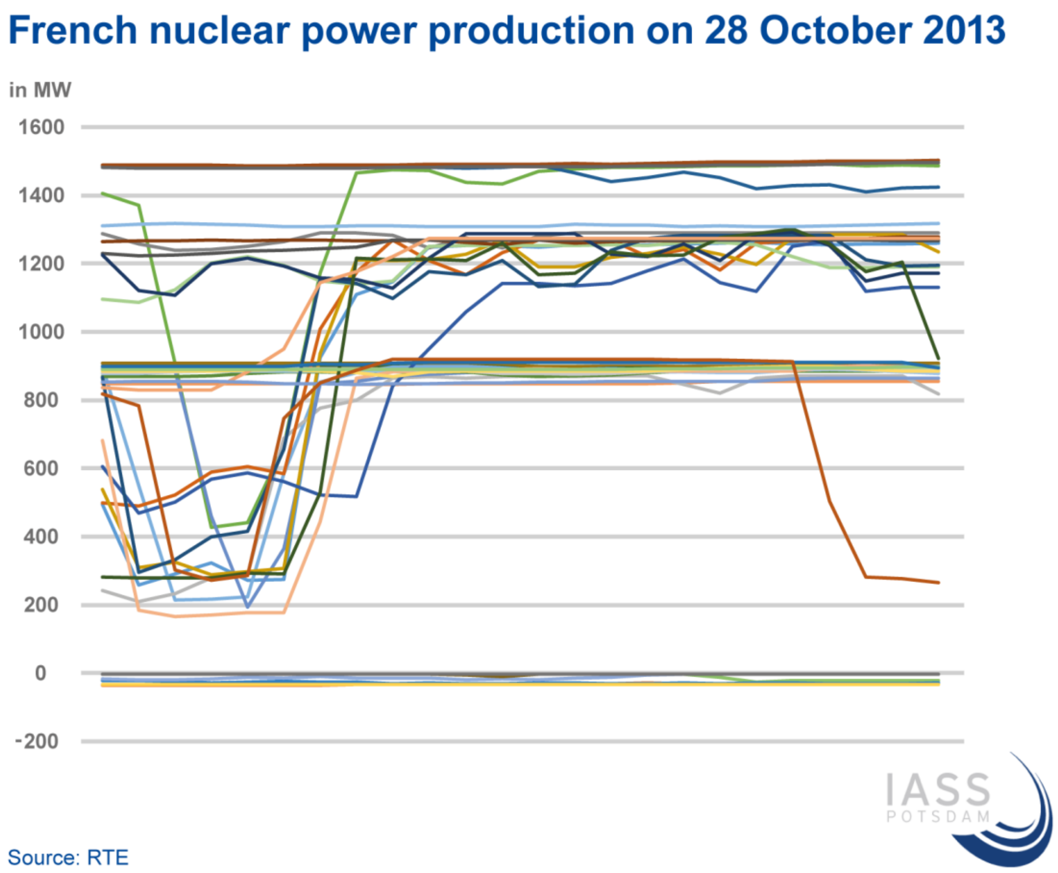


Figure 13: Unit-wise power production by the hour on 28 October 2013 for the entire nuclear fleet in France. While more reactors ramp here than in Figure 12, the rated capacities for most are clear to see. Data from Réseau de Transport d'Électricité 2014.

Buchan himself says the following about the "marriage" of nuclear and renewables: "If, in designing a country's ideal electricity mix, one had to choose an ideal source of backup electricity for intermittent renewables, you would not choose nuclear power." He adds that France is nonetheless "fated to try to integrate nuclear and renewable power" because of its plans to reduce the share of nuclear by 25 percentage points by 2025.[23] Although this plan was first announced in 2012, no significant reduction has yet taken place. Buchan speaks of "the likelihood… that France will neither replace its current reactors nor terminate them prematurely, but run them for as long as possible, up to 60 years for some reactors."

[23] France could also meet this target, which is expressed only as a percentage of demand, by raising power demand without closing any reactors. For instance, mobility and heat could be electrified.

Like most other writers, Buchan's main concern is not, however, technical, but economic; nuclear reactors simply provide the cheapest power when they run all the time. "French reactors have considerable experience in load following," he reiterates the common claim without providing any evidence. But if France were to replace 25% of its nuclear power with wind and solar by 2025 or even later, the French fleet would need to react to a far greater extent than ever seen anywhere. France would then have even more fluctuating wind and solar than Germany now does – and Germany has already had several peaks of around 90% renewable electricity. The present author therefore concurs with Buchan that France is unlikely to replace 25% of its electricity with renewables and agrees in general that the economics of combining nuclear with fluctuating wind and solar is a bad option. But Buchan overstates the case for nuclear.

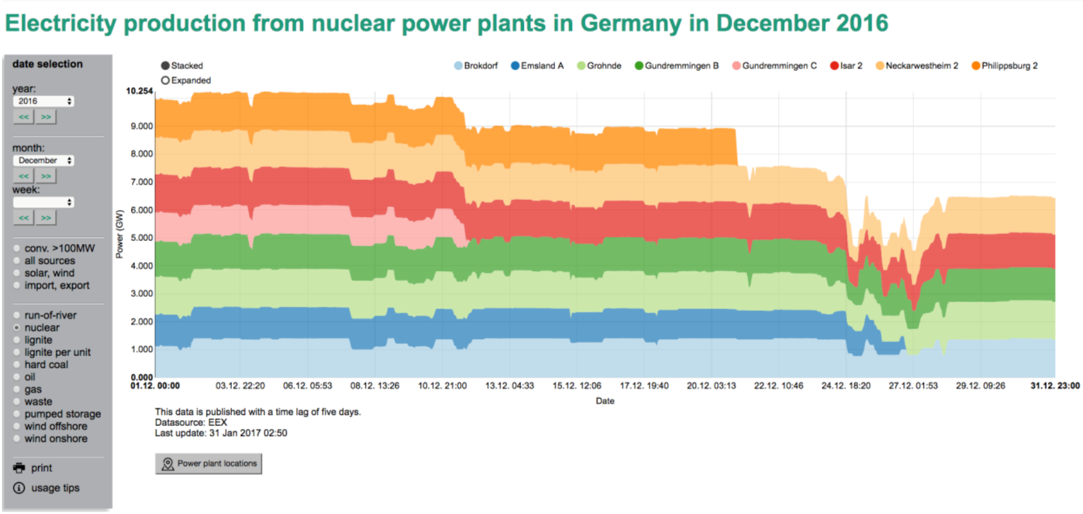


Figure 14: Power from German nuclear plants in December 2016. Copyright: Fraunhofer ISE.

For instance, Buchan claims, again without any evidence, that German "nuclear operators have learned to load follow when surges of renewables have driven electricity prices below the marginal operating costs of their reactors." In fact, nuclear has proven astonishingly unresponsive to price signals.

In a paper investigating power generation and wholesale prices, Fraunhofer ISE found (Figure 15) that German nuclear reactors were less responsive to negative prices than the country's lignite, hard coal, or gas fleet were (Meyer 2014). For instance, when intraday prices fell to minus 53.6 €/MWh on 16 February 2014, the nuclear fleet still ran at 71.7% of capacity – compared to 50.7% for lignite, 12.7% for hard coal, and 11.9% for gas (some gas and hard coal plants are also used in the power sector as a part of district heat, so they continue generating a certain amount of power because of heat demand regardless of power prices).

Here, we see that hard coal plants ramp the most and are very price-sensitive. From a technical perspective, one would expect gas turbines to ramp more, but they are uncompetitive based on price and thus generally only ramp *up* once hard coal plants have maxed out. The lignite fleet also ramps a bit, dropping to around 50% of total output once prices drop into the negative. But Germany's nuclear fleet never fell below 70% of output regardless of how low prices got. Indeed, on several days one finds the nuclear fleet running closer to 80% of rated output even though the spot price has fallen below minus 50 €/MWh – easily 80 €/MWh below the "marginal operating cost" of nuclear Buchan mentions.

Pertaining to the storm on 28 October 2013, Buchan quotes a French economist saying that “nuclear is flexible enough, and much more so than coal or lignite” from a technical perspective (just not an economic one). Germany is already testing that thesis, and the results from the scatterplot above suggest that nuclear reactors did not want to react to the negative prices reached during these timeframes, which are apparently too short for the reactors. Negative prices lasting weeks might be long enough; days are not. The German nuclear fleet seems to have already reached its technical limits for load-following.

We also already know from Germany what 20% fluctuating wind and solar (two thirds of which is wind; one third, solar) looks like: it peaks quite regularly above 50% of demand. Such peaks are only possible in Germany because the share of nuclear was reduced in 2011 from around 30% of demand to below 20% (and below 15% in 2016 and less than 12% in the first half of 2017), with hard coal plants additionally ramping as a fleet to an unprecedented extent. France does not have this option.

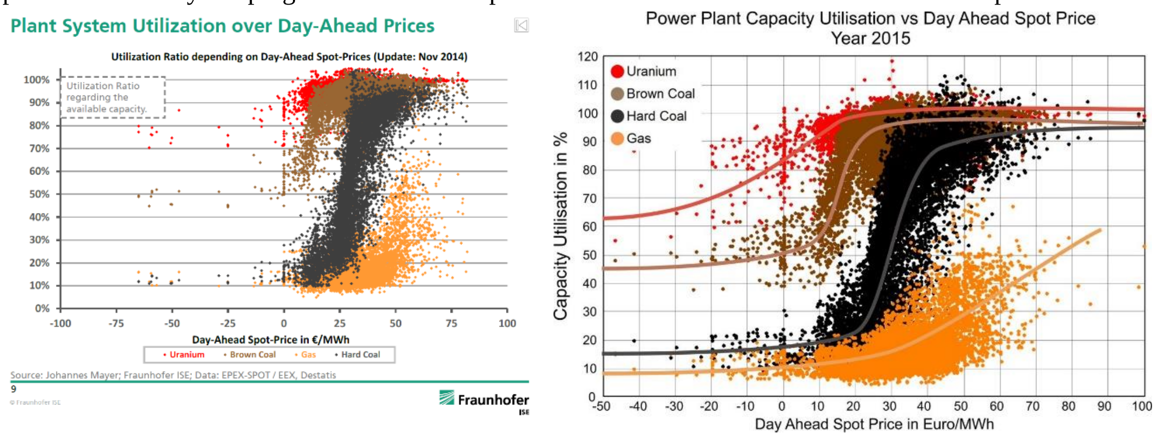


Figure 15: Scatterplot (left: most of 2014; right: 2015) of power generation levels relative to power prices by generation unit in Germany. The level of flexibility shown by German nuclear reactors in 2015 is greater than in the previous year, but nuclear is still less flexible than coal and gas power generators. Specifically, nuclear's reaction to negative prices is still the most limited. Copyright: Fraunhofer ISE.

3.2 Scenarios for France's plans to reduce nuclear power

Political targets are often nice-sounding rounded numbers, such as “20% by 2020.” Purely scientific pathways are more likely to sound like “19% by 2023,” which does not make for good campaign slogans. Furthermore, former French President Hollande did not have any scientific scenario on which to base his political proposal for a one-third reduction in the share of nuclear power. For political scientists, this fact is not surprising: energy targets often elicit the scientific investigations most people assume the policies are based on.

Aside from Buchan's brief investigation from the UK on France goal of 50% nuclear by 2025, however, there are only a few such investigations about France's nuclear reduction plan. Admittedly, RTE immediately produced a scenario (called "nouveaux mix") in 2012 for 50% nuclear but for 2030, not the official reduction year of 2025. Although it was assumed that wind capacity would reach 40 GW and solar 30 GW, the effect of ramping was not mentioned. The scenario assumed that the share of power from natural gas would also increase, thereby raising – and this seems to be the intended political finding – CO2 emissions from 26.7 to 30.8 Mt.[24] When the French government decided in Nov 2017, shortly before the present study was completed, to postpone ist nuclear reduction, Ecology Minister Hulot specifically cited RTE's renewed warnings that carbon emission would rise; the

[24] See in particular the table of TWh on page 137: Bilan prévisionelle 2012. RTE.

potential technical impossibility of significant nuclear ramping was again not mentioned -- because it has not been investigated (Wakim 2017).

Other scenarios came from négawatt, an independent group of French researchers,[25] and from IDDRI.[26] Arguably, ADEME's (initially suppressed, see Morris 2015) investigation of 100% renewables by 2050 also falls into this category (Ademe 2015). It should be noted, however, that France does not have a plan to completely phase out nuclear: "The official strategy is to maintain nuclear as a central – but no longer predominant – source, while freeing-up more room for renewables." (Mathieu 2016)

Still, from the German perspective, the number of subsequent studies of France's official goal seems quite low. The French are not complaining of a "slew of studies serving a particular clientele." Rather, there is relatively little discussion at all. In contrast, Germany is conducting a lively debate on its energy transition with input from many different sources.

What's worse, all of the French studies mentioned above skirt the issue of nuclear ramping – so central to the German debate. In the study focusing on 100% renewables, ADEME does not investigate how the nuclear fleet would need to ramp on the path towards that goal. Négawatt simply plugs in numbers of TWh for wind and solar power without discussing the impact on the nuclear fleet's capacity factor. Finally, IDDRI shows a gradual reduction in nuclear power, much of it being replaced by electricity from fossil sources, not by wind and solar. Otherwise, the flexibility of France's nuclear fleet is outside the scope of IDDRI's investigation.

One exception is (Cany 2016). Their paper economically models the French nuclear fleet being pushed down to 40% of rated output. The authors obviously did not look at the actual ramping behavior of the French nuclear fleet (sacrificing one so that others remain unchanged): "nuclear can contribute to load-following, especially in France since large variations in production can only [sic] be achieved by small increments in each power plant." Otherwise, the authors write that 30% fluctuating renewables would bring the capacity factor of a 60 GW fleet (France currently has 63 GW) down to 58%, close to the 57% capacity factor at which nuclear becomes uncompetitive economically even with an assumed carbon price of 30 euros per ton. The 30% share of fluctuating renewables in (Cany 2016) is close to the percentage France would have if it replaced 25% nuclear (as planned) with wind and solar power.

One option, of course, is that renewable power could be curtailed. As a result, the impact of negative prices on the nuclear fleet would be mitigated; in return, renewable power generators would forgo income or, if they are paid anyway, a higher cost impact would be passed on to ratepayers. The TAB study estimated that profits for nuclear plants would rise per installed megawatt from 180,000 euros to 330,000 euros per year by 2030 if renewable power is curtailed. The study concludes what proponents of renewables suspect: "If nuclear plants have limited flexibility, owners of these plants therefore have a great interest in having priority renewable energy dispatch revisited." In other words, there will be a political showdown over what should be curtailed first: nuclear or fluctuating wind/solar.

3.3 Wear and tear on reactors from ramping

The TAB study points out that three reactors had run in load-following mode quite regularly in 2009. What is salient about these reactors – though the study does not mention it – is that they were all quite old. The literature usually focuses on the seven Convoy and Pre-Convoy reactors when discussing

[25] https://negawatt.org/Scenario-negaWatt-2017

[26] See Figure 13a in "The transition of the French power sector by 2030: an exploratory analysis of the main challenges and different trajectories" by Andres Rudinger et al.

flexibility, for instance. The three reactors in the TAB study were neither. What they have in common is that they were running out of time under the original phaseout of 2002. Each one had an allotted number of kilowatt-hours to generate and would run out of those hours soon: Neckarwestheim 1 in late 2009, Phillipsburg 1 in 2011, and Unterweser in 2013. With the elections on the horizon, utilities began running these reactors less often starting in 2007.[27] The goal was thus not to follow loads at all, but to run at lower capacity in order to stay in operation long enough for the new government to have time to extend reactor commissions. This fact does not change the interpretation of these reactors' performance; clearly, they were able to run in this mode of "limited flexibility." However, the impact of this mode of operation on these three facilities may never be known; they were all switched off as a part of Merkel's phaseout of 2011.

Does load-following wear down a reactor? The question is often raised and is hard to answer for a lack of significant load-following to date (Totz 2011). As (Bruynooghe 2010) put it: "no significant effect have been observed or could be quantified since no systematic study has been made in this topic."[28] The experts quoted in the TAB study say that even less damage has been found than would be expected from the literature. There are cases when a reactor that has been ramping experiences a lot malfunctions, but reports never clearly state that the ramping was the cause (see the case of Civaux 1 below).

One exception is Germany's Brokdorf. Indeed, it seems to be the only reactor in the world for which damage from load-following has been reported as the cause. In February of 2017, excessive corrosion was detected on the fuel rods during a routine inspection. In July, the officials reported that frequent, extensive ramping was the reason. The reactor was allowed to go back online, but only within a certain operating range (safe mode) that excluded further load-following (Spiegel 2017). A look at the data for power production at the reactor leading to the damage reveals, however, very little load-following at all (see Figure 16 below).

Though such statements are rare, one does occasionally find a nuclear expert stating openly that ramping is a technical issue, not just an economic one. For instance, in an interview published on 1 March 2011 (just 10 days before Fukushima) the president of the German Atomic Forum stated the following:

> "In a nuclear reactor, especially in the primary circuit, there are high temperatures and pressures. Major changes would cause wear and tear. The area below 60% is not desirable.... We are not talking about economics here, though that does play a role... It's a technical issue." (Güldner 2011)

[27] In their history of the German nuclear sector, Radkau and Hahn specifically list Phillipsburg 1, Unterweser, and Neckarwestheim 1 as reactors whose owners "attempted to drag out the deadline for the closure of the facilities beyond the elections of 2009. In doing so, they resorted to such tricks as reducing power generation, conducting comprehensive revisions, scheduling extended periods of standstill, and upgrades." (Location 6877) Also scheduled to close in 2009, Biblis A and B were simply taken off-line for more than a year so that some 15,000 dowels could be replaced. Note that merely leaving some of the allotment until after the elections would not suffice; it was not until the fall of 2010 that Merkel's new government officially extended reactor service lives, and it was unclear how long that would take in 2009.

[28] The same study adds: "Recently EDF conducted a study aiming at quantifying the loss of production due to outages related to load-following operation mode. Details of the study are confidential…"

Likewise, the US Department of Energy's grid reliability study for Energy Secretary Perry (DOE 2017) points out that "the expected forced outage rate for generators in {ISO-New England} regions have increased because power plants in the region are operating under more stressed conditions. Older power plants in each region are less reliable and go out of service more often as they age." Though nuclear reactors are not specifically mentioned, it is unclear why they would not suffer from the same aging issues that other power plants face. Indeed, the DOE report also states: "ramping a nuclear plant will also result in more wear and tear due to thermal gradients and mechanical stresses and will likely increase capital expenditures."

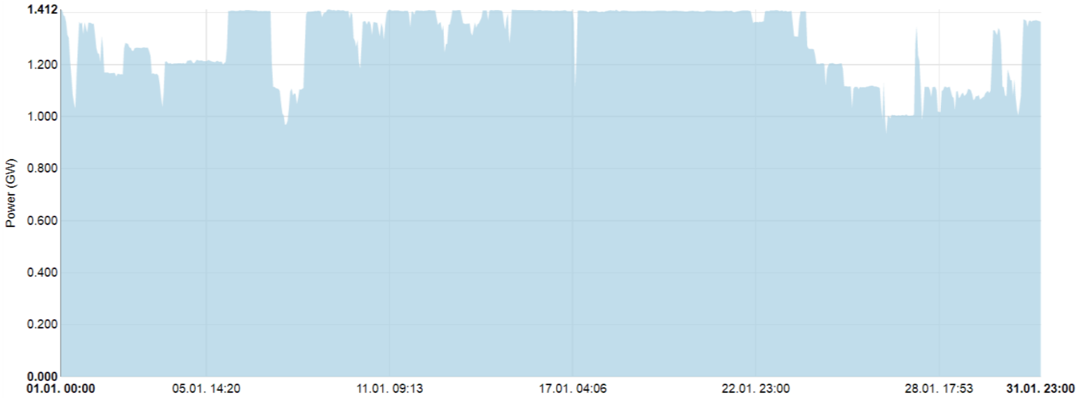


Figure 16: The ramping that broke Brokdorf – power production at the reactor in 2016. The plant obviously ran at reduced output over extended times frames, but it did not ramp up and down by more than around a third. Yet, this level of ramping broke the reactor. Copyright: Fraunhofer ISE.

3.4 The flexibility needed for solar and wind

Most of the studies focusing on the incompatibility of nuclear with fluctuating renewables highlight wind power, downplaying solar because there was so little at the time. But in fact, the capacity factors of wind power are increasing, which will alleviate the conflict somewhat. With photovoltaics, however, most electricity will always be generated within a six-hour timeframe (9 AM to 3 PM), and no electricity and all will be generated 12 hours a day. The only German study from 2008-2011 – the years of the *Systemkonflikt* debate – that highlighted solar was published by the Arrhenius Institute in August 2010 (Bode 2010). It focused on "the impact of the massively increasing PV capacities on the economics of conventional power plants." In 2010, Germany would install 7.5 GW for the first time, a performance that was repeated in 2011 and 2012. To understand how fast that growth was, consider that, by 2012, Germany had reached the level of PV capacity assumed in the 2008 *Leitstudie* for 2050.

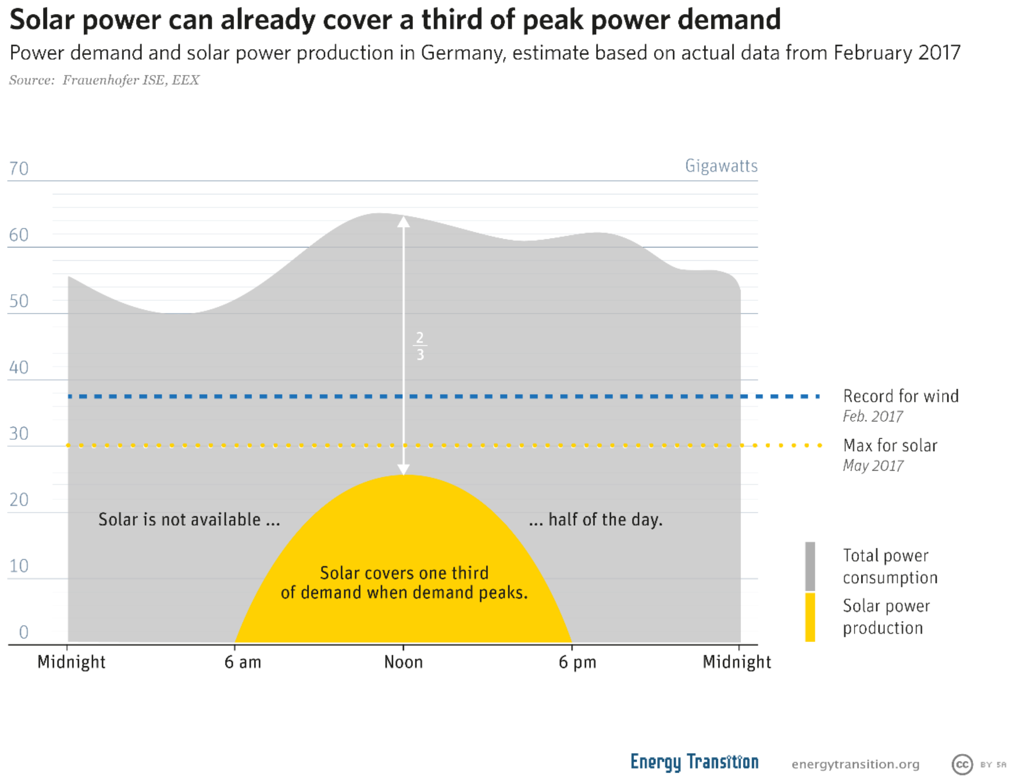


Figure 17: Solar power generation generalized based on data from February in Germany. Solar spikes for just a few hours and will leave little space for conventional power many days a year by the time solar covers 10% of German demand. Source: EnergyTransition.org. CC BY SA.

Nuclear plant commissions would be extended in 2010, and solar was now growing beyond everyone's expectations. Against that backdrop, Arrhenius' discussion paper argued that German policymakers would have to start addressing the consequences of the rapid solar buildup for the rest of the power sector or "try to slow down" solar growth. While the authors did not focus on nuclear specifically, they argued that "a mere extension of the remaining production for a nuclear plant is not a solution, but will exacerbate the problem." They added that "nuclear power plants are not well-suited to follow" rapid load changes caused by solar (and wind).

In a study from March 2014, Ecofys writes that a nuclear reactor can only have 400 cold starts over its service life (Ecofys 2014). One per year is generally needed for refueling, but if such a reactor had to switch off for several days a month to make space for fluctuating wind and solar, the plant would have to close after 33 years of operation. If it had to cold-start every week, it would not last eight years at that rate.

Perhaps the most cited comparison of the dispatchability of nuclear, coal, CCGT, and OCGT is the following table from joint study by the OECD and the NEA (OECD 2012):

Table ES.1: The load following ability of dispatchable power plants in comparison

	Start-up time	Maximal change in 30 sec	Maximum ramp rate (%/min)
Open cycle gas turbine (OCGT)	10-20 min	20-30%	20%/min
Combined cycle gas turbine (CCGT)	30-60 min	10-20%	5-10%/min
Coal plant	1-10 hours	5-10%	1-5%/min
Nuclear power plant	2 hours - 2 days	up to 5%	1-5%/min

Source: EC JRC, 2010 and NEA, 2011.

Table 2: Load following at coal, gas, and nuclear power plants. Copyright: OECD 2012.

Here, we see the comparison missing in the aforementioned IER study: nuclear ramps the least of all conventional power sources. What's still missing here is the must-run level. For nuclear reactors in Germany and France, it seems to be around 50% of capacity and as low as 20% under certain constraints. For coal plants, 25% is a fair estimate of minimum load in new hard coal plants, compared to 50% for lignite (Consentec 2016, Brauner 2011). If a coal plant goes cold, it requires oil to restart. For gas turbines, cold starts are less of an issue; there is no technical constraint on the number of cold starts, and startup times of a quarter of an hour should suffice to complement fluctuating renewables given the good predictability of wind and solar.

At a mere 20% wind and solar power at the end of 2016, Germany is quickly approaching a point when renewable power will require all conventional capacity to shut off for many hours at a time. The "dental chart" below, first popularized in 2010, shows an extrapolation of the situation from May 2012 for May 2020. The residual load (gray area on the right) disappears on a Sunday at a time of low demand and high solar power production.

In Germany, the impact of solar on the conventional fleet will, as predicted by the Arrhenius Institute, be more severe than the impact of wind power. More solar is generated in the summer, when power demand in Germany is seasonally low. Countries with higher summer demand (because of air-conditioning, etc.) will be able to absorb more solar power without the need for curtailment/storage.

Even at a mere 6% of demand over the year, solar peaked at 30 GW in May 2017. By the time it makes up 10%, PV will be peaking on exceptional days above 40 GW. Moving beyond a 10% share of solar power in Germany will increasingly require storage or curtailment. Baseload capacity will have to disappear by then; otherwise, S&C requirements will occur even earlier, thereby raising the total cost. German economists (Hirth 2015) have calculated that a 40% share of fluctuating wind and solar will mean that "virtually no baseload generation is left." A mere 10% solar in countries like Germany, Belgium and France would force nuclear plants to ramp regularly beyond their rated ability.

If fluctuating renewables are an "enemy" of nuclear, then solar is a bigger enemy than wind power. Researchers have paid more attention to the impact of wind power on nuclear, however; this oversight could be explained years ago by the insignificant share of solar power in supply, but future studies should focus more on the impact of solar power.[29]

[29] One example is a study from 2014 on wind power's impact on France's nuclear fleet. While France has great wind potential, it is also a good country for solar power, so the oversight is not justified by geography.

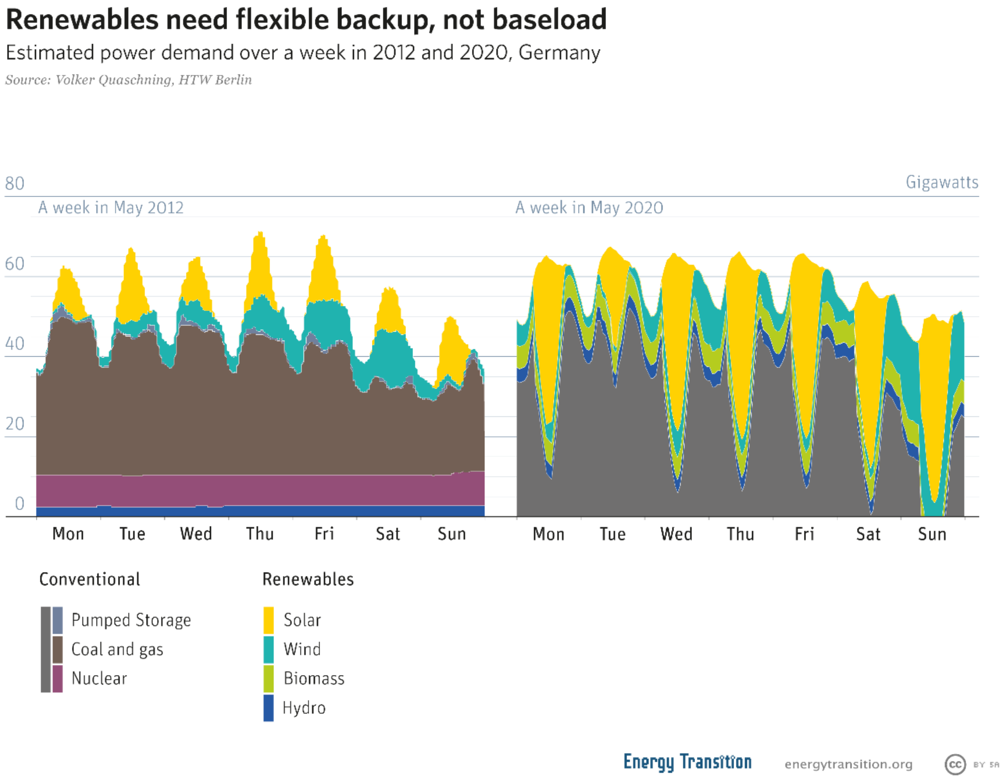


Figure 18: By the end of this decade, Germany may reach levels of solar power generation than will largely wipe out the need for baseload power. Source: EnergyTransition.org. CC BY SA.

It will be politically difficult to stop solar power at 10%; there are simply too many different investors who can install it. One German study (BMVI 2015) found, for instance, that roof-mounted solar arrays on only two thirds of suitable roofs would add up to 65 GW, enough to cover 10% of demand. This figure does not even include ground-mounted, utility-scale solar plants. If nuclear is to play a part, utilities would thus need to look for a way to prevent homeowners and businesses from installing solar. And that is exactly what many of them are doing across the United States – to protect their baseload assets (Garfield 2017, Warrick 2015).

3.5 California's "excess renewables"

Unlike Illinois and New York, California has decided to ramp up renewables and close the state's only remaining nuclear plant when its license expires in 2025. Nonetheless, the widespread understanding in California is that fluctuating wind and solar are causing problems for other power sources. The "duck chart" has become famous in this discussion; it shows (see below) how the residual load (often called the "net load" in the US) is shrinking at midday, primarily due to the increase in solar power.

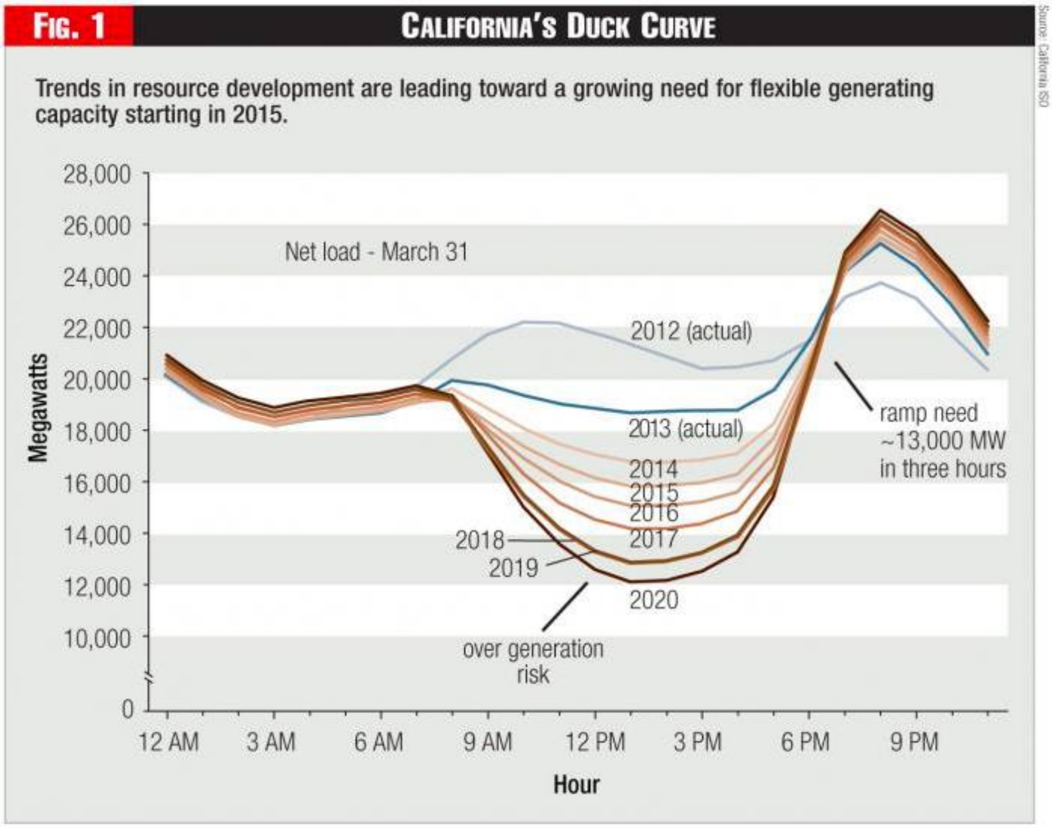


Figure 19: California's "duck curve" with a truncated Y-axis making the upward ramp in the late afternoon seem larger than it really is. Copyright: [California Independent System Operator](#).

Unlike Germany, California has a larger share of in-state solar generation that of in-state wind power.[30] One major difference between the two jurisdictions is that California is a major importer of electricity; in 2016, imports made up around a third of the state's power consumption. In contrast, German power exports hit a record high in 2016 at around 8% of generation, with Germany overtaking France as the largest net exporter in Europe. In California, solar power made up nearly 10% of in-state generation and covered 8.1% of total supply that year, including power imports. In Germany, solar roughly covered 6% of demand and generation. However, the total level of fluctuating wind and solar is comparable in California and Germany at roughly 1/5 of generation.

We find Californian energy experts, such as the Energy Institute at Haas (Wolfram 2017), complaining about there being "too much renewables":

> "What do the negative prices tell us? At a fundamental level, they tell us that we have too much of a good and suppliers need to pay people to take it off their hands. Right now, California has too much renewable electricity."

This interpretation gets picked up in the press. For instance, the Los Angeles times wrote in June 2017 that "California invested heavily in solar power. Now there's so much that other states are sometimes paid to take it." (Penn 2017)

[30] The state imports a lot of wind power, and a significant amount of in-state and solar generation is distributed and therefore not always included in official figures reported. See: http://www.energy.ca.gov/almanac/electricity_data/total_system_power.html

From the German perspective, this reading is not mandatory. To begin with, the duck chart above has a baseline of 10 GW, not 0 GW. The duck is thus in a deep lake, not about to drag its belly through the mud. The Haas article shows (Figure 20) the share of renewables covering around half of demand for some five hours on 9 April 2017. Power imports dropped the most, though they do not disappear entirely. Coal power was the second largest single source reported in 2016 just behind wind power. However, nearly half of all power imports to California were "unspecified sources of power." In all likelihood, the share of conventional electricity imported is therefore significantly higher since wind power imports are likely to be specified for political reasons (toward target fulfillment).

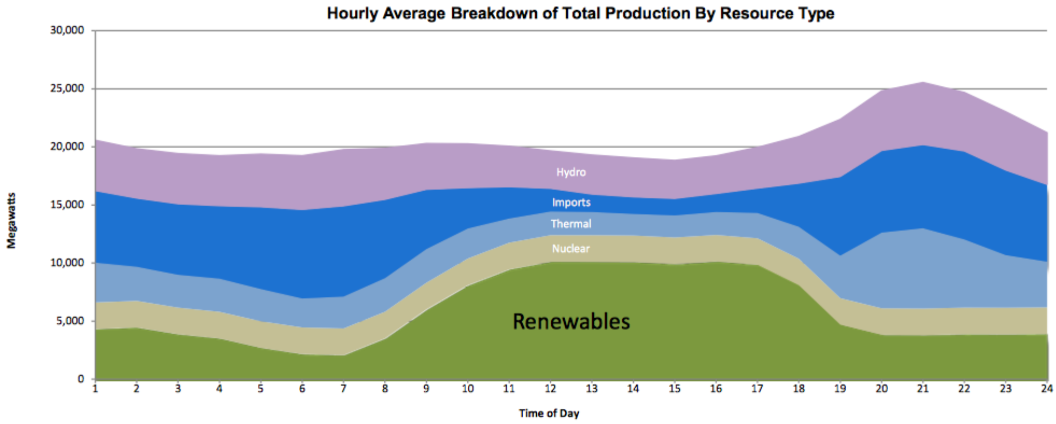


Figure 20: Power supply in California on 9 April 2017. Renewables mainly offset imports, much of which is coal power. Copyright: California Independent System Operator.

Renewable electricity is also already being curtailed. On 26 March 2017, for instance, 8.5% of the power generated by utility-scale solar projects was thrown away; nuclear did not change its output significantly. At the same time, power imports, which fluctuated the most that day, did not drop below 3 GW (Paulos 2017).

From a German perspective, the amount of solar curtailed is quite high given that overall generation excluding fluctuating wind and solar only fell from around 20 GW to 13 GW. The German conventional fleet already ramps down much more without renewables being curtailed. Indeed, the solar curtailments in California began in the chart below when conventional capacity had been pushed down to only 18 GW.

Similar situations are quite frequent in Germany as well, but the interpretations are different. Because nuclear power is already scheduled to be shut down by the end of 2022, the focus is now on getting rid of coal power. The goal is to have at least 80% renewable electricity by 2050, so everything else is arranged around that goal – meaning that there is no talk of "too much renewables." More specifically, negative prices and the need for storage/curtailments are always spoken about in terms of the conventional fleet's inflexibility.

For instance, on 30 April 2017 German coal plants were pushed down to 8 GW – a record low. Hard coal plants fell from 7.7 GW to 1.8 GW (earlier in the week, they had run closer to 19 GW). Lignite dropped from 16.4 GW to 6.2 GW. In contrast, nuclear plants only fell from 7.9 to 5 GW;[31] once again, it seems hard for a nuclear fleet to ramp by more than around one third. Spot market prices fell to minus 215 €/MWh. It was a Sunday on a long weekend, and the following Monday was international

[31] These data can be viewed at Energy-Charts.de. The Agorameter also visualizes data from the German power sector, as does Smard.de. These websites are all interactive; you can (within various limitations) customize the view. There is no such equivalent for California, nor anywhere in the US. The EIA's visualizations lack the detail and customization of the German websites.

Labor Day (May 1). Demand was thus low, while both wind and solar were high, with renewables reaching 55.2 GW and demand coming in at only 67 GW.

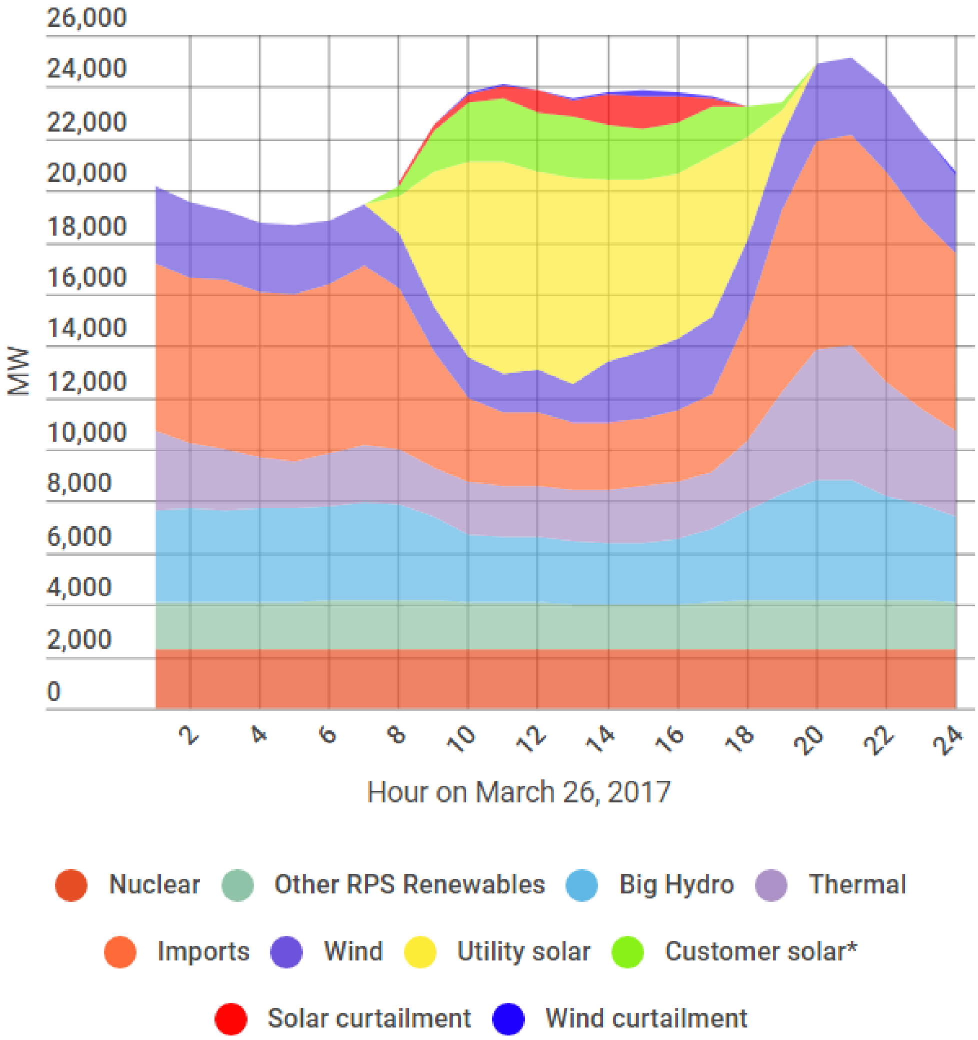


Figure 21: The impact of solar on the duck curve when the baseline is zero and the Y-axis is not truncated. Copyright: Greentech Media.

The low of renewable power production was 16 GW at midnight that day, and renewables made up 64% of German power supply over the course of April 30. That percentage is in line with the 65% scenario discussed above; the Germans thus already know from experience what such a situation will look like, and they conclude that baseload must go – not that they have "too much renewables."

The communications director for Agora Energiewende, an independent think tank with foundation funding, stated the following in a press release on this event (Agora 2017):

> "We will encounter such constellations more frequently, and they will be unexceptional by 2030. Inflexible power plants will then no longer play a role in power supply; they would

only ruin prices. By 2022, the nuclear phaseout will be finished, so nuclear will no longer pose a problem in 2030. But in addition, inflexible old lignite plants must be the focus of attention."

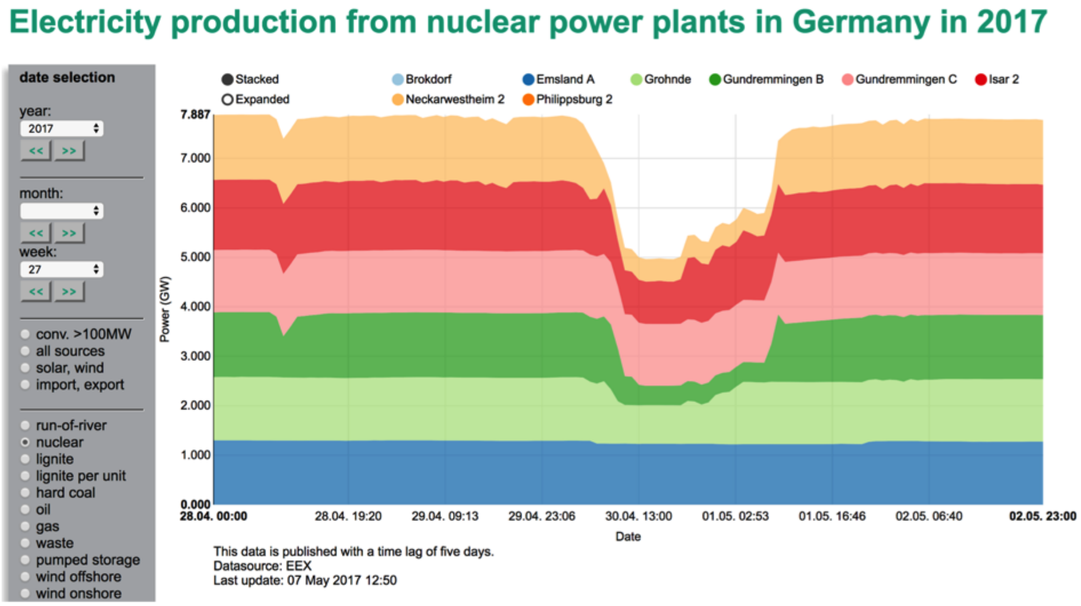


Figure 22: Germany's nuclear fleet ramped by only around a third even though wholesale prices dropped below -200 €/MWh. Intraday prices (weighted average) went negative at 8am on 30 Aril 2017 and remained negative until 10 am the next day. Copyright: Fraunhofer ISE.

Here, we see that inflexible baseload is considered the problem – the cause of negative power prices. As described above, this opinion has been mainstream for nearly a decade. In 2013, researchers from Fraunhofer ISE also published a paper (Figure 23) showing that the need for storage (or curtailment) begins at around 35 GW of installed wind and 50 GW of installed solar (the 100% curve in scenario 1) if the must-run level is 20 GW, roughly where it is today. If that level is reduced to 5 GW, however, closer to 60 GW of wind and 80 GW of solar could be installed (scenario 3). Notice as well that 99% of the wind and solar power generated would not need to be stored/curtailed in scenario 3, with nearly 100 GW of wind and around 120 GW of solar installed – more than twice the current level of each (Kreifels 2014).

In March 2017, Germany's Network Agency published its own report on must-run capacity (BNetzA 2017). It sees things very much the same way. First, it put the level of must-run capacity in 2015 at between 18.8 and 23.6 GW; Fraunhofer's estimate of 20 GW lies in the middle of that range. It adds that the level of conventional capacity needed for grid stability was around 3.2 to 4.6 GW – far less than current must-run levels. This number may seem quite small; after all, we repeatedly read that rotating masses will always be needed to stabilize the grid – which is true, only that we apparently just need less than a sixteenth of peak demand (around 80 GW in Germany) for that purpose.

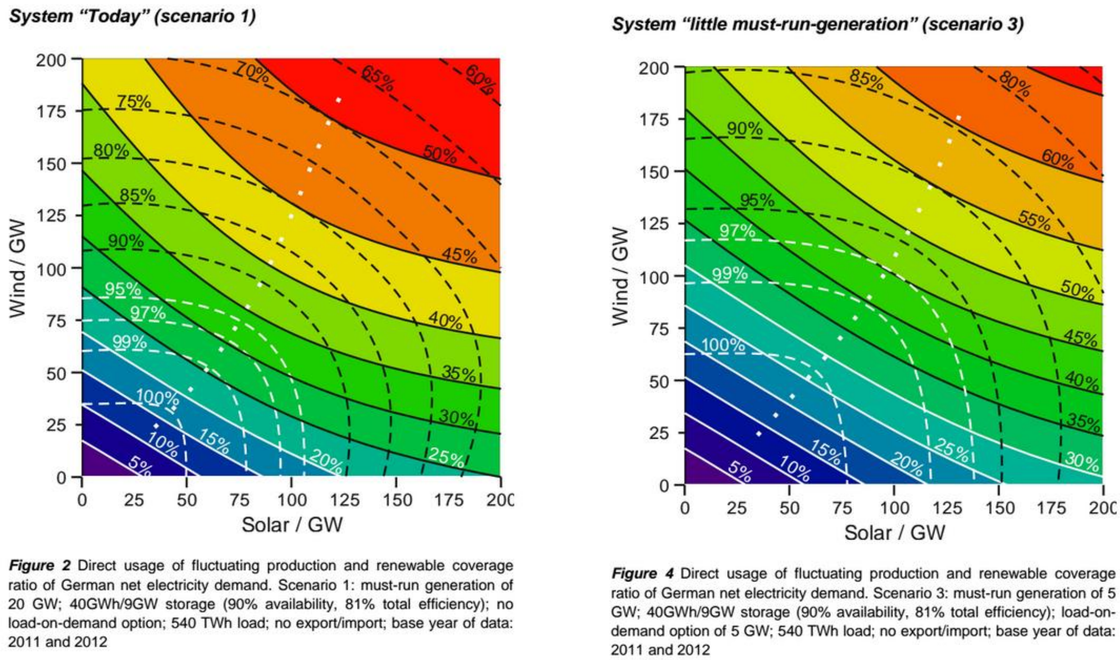


Figure 23: Isobars showing the level of solar (X-axis) and wind (Y-axis) that could be installed without the need for storage. The percentages on the dotted lines represent the amount of solar and wind power that can be consumed directly without storage. The percentages on the bold line show the share of wind and solar in German power supply. Reducing must-run capacity offsets the need for storage. Copyright: Fraunhofer ISE.

The report's executive summary begins thus:

> "The German government's long-term goal is a carbon-free, non-nuclear generation structure. Efforts must therefore be made to reduce, to the extent possible, the share of conventional generation that is required for supply security but does not respond to price signals."

In its parliamentary response to the Network Agency's report, the German government writes:

> "As a part of the optimized power market 2.0, the government aims to increase the flexibility of generation and remove obstacles towards lowering must-run capacity."

In a previous paper investigating the cause and effect of negative power prices, (Agora 2014) wrote: "In short, the cause is a lack of flexibility in the power sector." (IASS 2013) explained negative prices on a Sunday: "For conventional power plants, such as hard coal and nuclear, negative prices can make economic sense. It is better for them to keep running then to switch off and then go back online on Monday." Epex, the electricity spot exchange for northwest Europe, agrees:

> "Negative prices are a price signal on the power wholesale market that occurs when a high inflexible power generation meets low demand. Inflexible power sources can't be shut down and restarted in a quick and cost-efficient manner. Renewables do count in, as they are dependent from external factors (wind, sun)." (EPEX 2018)

In other words, while Californians say "too much renewables" causes negative prices, the German (and increasingly European) view is that conventional baseload is too inflexible to respond to reductions in the residual load brought about by renewables. California aims to have 50% renewable electricity by 2030 – the same target Germany has for that year. It makes little sense for Californians to claim they already have too much renewables since the official goal is to add more.

4. What gets overlooked in cost discussions

4.1 Capacity factors impact costs significantly

Cost estimates vary greatly not only for nuclear but also for solar and wind. For instance, resources play a great role; sunny areas simply have cheap solar power, and windy areas have cheap wind power. In 2014, solar reached a record low of 0.059 USD/kWh in Dubai, which was considered a breakthrough. But in fact, the region has twice as much sunlight as Germany does; yet, German feed-in tariffs for the largest arrays had already fallen to around 0.09 USD/kWh that month. When adjusted for insolation conditions, Germany thus still had cheaper solar power than Dubai did in 2014, but Dubai was celebrated simply because the number was lower. Similar examples could be given for wind power. Estimates of total system cost therefore have to take account of regional specificities.

For nuclear, the situation is different because the cost does not depend on the weather. Nonetheless, cost estimates here are hard to come by. French President Emmanuel Macron famously stated (Sollety 2017): “Nobody knows the total cost for nuclear energy. I was minister for industry, and I could not tell you.” But the main mistake that studies of deep decarbonization with a mixture of nuclear, wind, and solar make is taking the simple LCOE as a price for nuclear without adjusting for ramping.

(Brick and Thermstrom 2016), for instance, do not specify the required flexibility of the fleet that would back up solar and wind, nor do they include the cost impact of lower capacity factors when nuclear reactors need to ramp. The only sensitivity they include is a “pessimistic” estimate for the capital costs of nuclear plants; along with the EIA’s assumption of $4,646 per kW, the study includes a scenario with a cost of $6,500 per kW. The pessimistic estimate is roughly 40% above the reference estimate, which may seem significant – but cutting the capacity factor of nuclear reactors in half would nearly double the cost of that electricity.

The cost impact of ramping is shown in screening curves. The chart below shows that nuclear requires a capacity factor of nearly 70% to be the least expensive conventional power source. Obviously, various assumptions are at work here, such as a carbon price making coal with CCS less expensive than without (NEA 2011). The point here is not to specify the capacity factor at which nuclear becomes uncompetitive in general, but rather to understand that studies investigating which mix of solar, wind and nuclear for deep decarbonization is the least expensive have to adjust for capacity factors, not be solely based on capital costs.[32]

(IDDRI 2017) includes the following chart comparing the cost of electricity from nuclear and CCGT at various capacity factors:

[32] See for instance Table A.1, where capital costs are assumed without any adjustment for capacity factors.

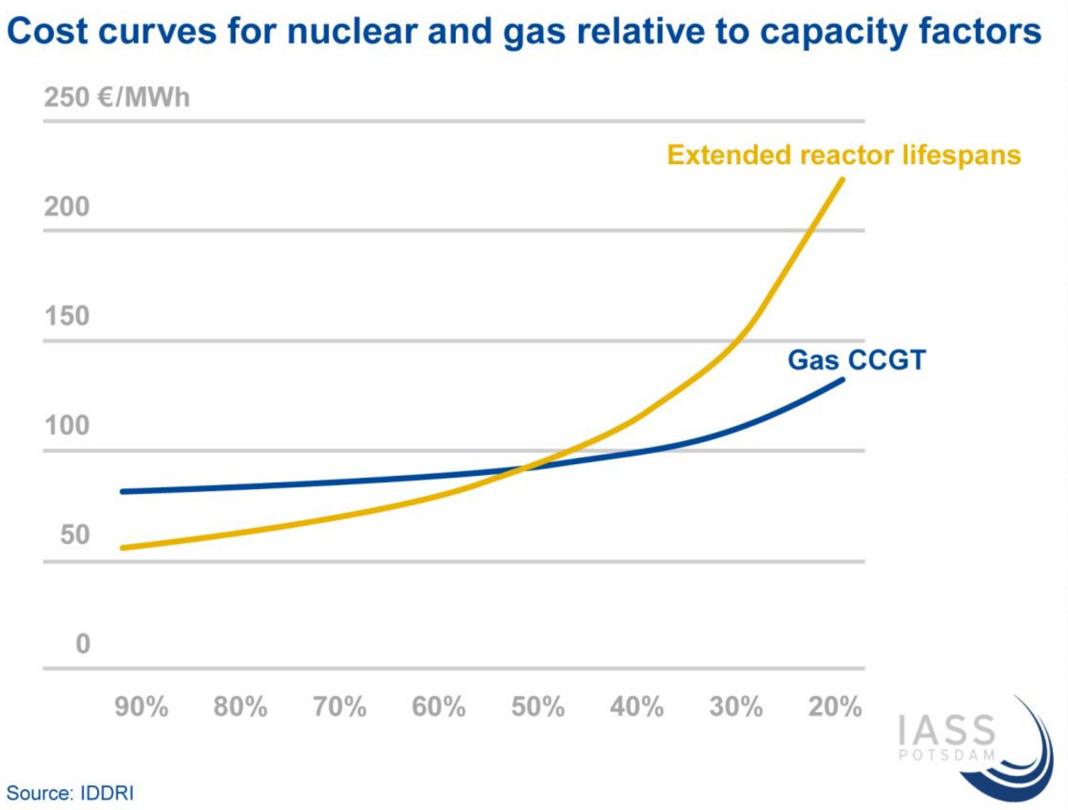


Figure 24: Nuclear power becomes more expensive than gas in France when the two have capacity factors of 50%. Note that this calculation assumes, among other things, a carbon price of 30 euros per ton on CO2. Source: IASS based on data from Institut du Développement Durable et des Relations Internationales.

At a capacity factor of around 50%, CCGT becomes increasingly less expensive – or, put differently, nuclear quickly becomes prohibitively expensive. (Remember that Cany et al., quoted above, argue that a capacity factor of 57% is needed for nuclear to be competitive under certain realistic assumptions.) The French fleet currently runs at an annual capacity factor below 80%, below the world average, because of the large share of nuclear in the country. However, the impact of ramping on the nuclear fleet is still quite small at an estimated 1.2% of capacity – another indication of how little the French nuclear fleet ramps, whatever its theoretical capability is.[33] The IDDRI authors conclude: "It seems hardly economically advisable to prolong the service lives of reactors beyond 40 years if the sole objective is to use them in load-following mode (and hence at a lower capacity factor). Investments in gas turbines would be generally less expensive even as they offer greater flexibility."

4.2 Belgian investigation makes nuclear look cheap

In 2016, PwC produced a 41-page study (PwC 2016) for the Belgian Nuclear Forum that exemplifies the problem. It investigates three scenarios with the goal of finding the least expensive one: no nuclear, 3 GW of nuclear, and 6 GW of nuclear.

The share of wind and solar power in all scenarios is the same: roughly 28% wind power and 5.9% solar in 2030. In recent years, Belgium has generated around 80 TWh of electricity but imported another 10 TWh, putting demand close to PwC's base year figure of 90 TWh. (Entso-e 2016), the

[33] "In France, where load following with the nuclear power plants is widely used, the impact of load following on the unit capability factor (IAEA, 2010b) is estimated to be about 1.2%." (NEA 2011)

European transmission grid operator network, puts the share of solar in Belgium at 4.7% in 2015, with wind power at 8.2%. (In contrast, Febag, the association of Belgian electricity and gas providers, has only 3.7% solar and 6.4% wind in 2016.[34]) To simplify the calculation, let's assume that Belgium had 7% wind power in 2016, so that the PwC scenarios assume a quadrupling.

The share of solar power would therefore not be able to double in either case as PwC limits it to 5.9%. Though the study does not mention it, policymakers would need to actively prevent citizens and businesses from installing solar if the country is to stay within PwC's limit. As mentioned above, an investigation in Germany found that the Germans could get around 10% of their electricity from solar arrays on only two thirds of suitable existing rooftops (BMVI 2015). Wind power peaks regularly in Belgium at some 1.5 GW (see the Elia website). If wind power quadrupled, it would thus regularly max out at around 6 GW in PwC's scenarios, which the study does not explain. The impact would be significant ramping for the rest of the fleet, which currently generates around 7.5 GW.

If natural gas switched off entirely (and if we leave out solar power for the moment), then nuclear would regularly be pushed down to 1.5 GW. The study assumes "third-generation reactors" but adds: "without a determination of whether existing plants are kept online or new ones are added." If Belgium has only 3 GW of nuclear regularly ramping to 1.5 GW, ramping from 100-50-100 is technically possible. But 1.5 GW is 25% of 6 GW – PwC's other scenario – so these reactors would regularly ramp at the maximum design capability of the best French reactors (100-25-100), and all other sources (solar, hydropower, natural gas, etc.) would simultaneously have to be completely curtailed. This scenario pushes the envelope, which the study does not explain.

The technical discussion is thus left out. But PwC doesn't address the impact of this ramping on the economics of nuclear, either. Only capital costs, O&M, fuel, waste, and a carbon price are calculated. Capital costs are relatively high for nuclear compared to coal and gas (CCGT and OCGT), but very low nuclear fuel costs compensate for that upfront cost. In other words, nuclear is cheapest when it runs a lot. The weak point in this analysis is the capacity factor (*taux de disponibilité*) of 85%, which is already slightly higher than in recent years in Belgium – and above the global average capacity factor. (The expected reactor age of 60 years also remains to be reached by any reactor worldwide, which makes the calculation even more generous in favor of nuclear.)

If these reactors have to ramp a lot to make space for wind and solar, nuclear power quickly becomes expensive, as IDDRI calculated for France. This effect of lower capacity factors is significant but completely ignored in PwC's analysis, which simply claims that "a mix of renewables and nuclear" would be best. The price of nuclear power is not adjusted to accommodate for a lower capacity factor in the 6 GW scenario, nor is there any calculation of the amount of (nuclear or renewable) electricity that would need to be curtailed – and what that cost might be.

[34] https://www.febeg.be/fr/statistiques-electricite, accessed 4 January 2018.

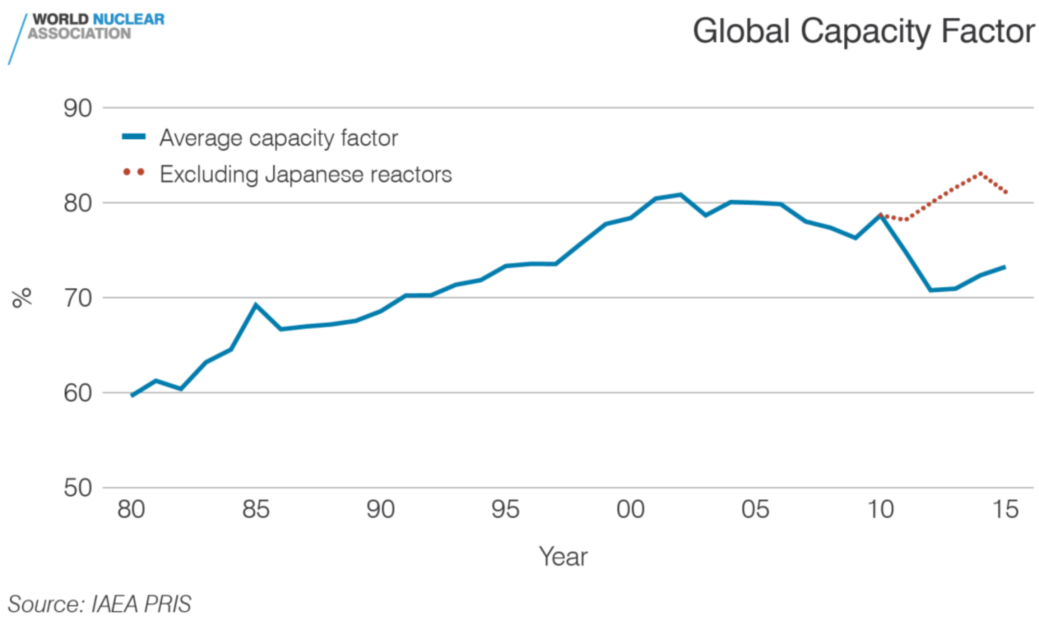


Figure 25: Capacity factors for the global nuclear fleet. Copyright: World Nuclear Association.

Adding in solar only makes the conflict worse. The 5.9% solar in PwC's scenarios is exactly the amount Germany had in 2016 – along with 13% wind power, roughly half the level in the PwC study. The German example shows (Figure 26) that solar power would peak at 30-40% of generation almost every day during the summer months as it does now in Germany. Double the green area for wind power, and you see that conventional generation basically disappears twice that month.

Nuclear reactors cannot ramp down to 0% regularly; they can only do so in an emergency mode, as described in the TAB study. PwC's assumptions up for the share of wind and solar thus completely rule out all nuclear power on a technical basis, a fact the study omits. The only other option is significant curtailment, which PwC does not investigate either.

PwC's study is especially egregious for leaving out the cost impact of lower nuclear capacity factors and the amount of power curtailed, but the price of nuclear is often calculated in such scenarios that include wind and solar without any account taken of nuclear ramping. Even those that speak explicitly of "flexible nuclear," like (de Sisternes 2016) do not adjust at all in cost estimates for a lower capacity factor when nuclear ramps (see Table A.1 there). Lower capacity factors are the most overlooked cost item generally in scenarios for future low-carbon power supply – and yet, this cost impact is the biggest variable for total system cost (Hirth 2015).

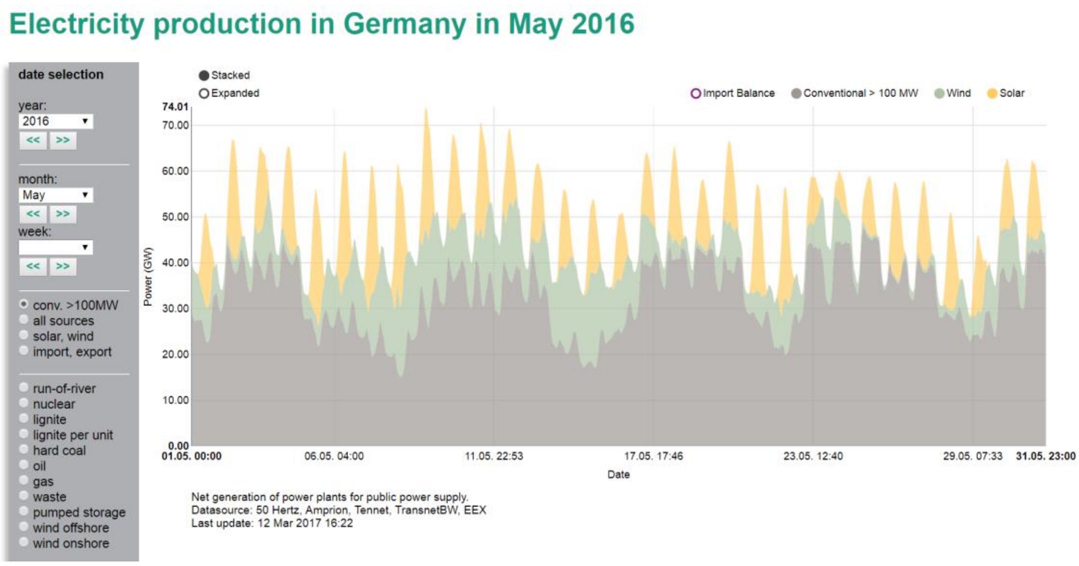


Figure 26: Power generation in Germany in May 2016. Solar and wind already push the residual load (grey area) down close to the power plant fleet's must-run level of some 20 GW. Copyright: Fraunhofer ISE.

For wind power, there is one mitigating factor: capacity factors are rising. Utilities are realizing the value of spreading wind power more evenly across the day instead of having it peak at higher levels. Manufacturers have developed wind turbines that have taller towers and larger blades (greater swept areas) without increasing generator size in proportion. The result is that wind turbines generate power more often; the trade-off is that peak power generation is lower than it could be with a bigger generator.[35]

For solar, the only option at the moment is tracking systems and installing arrays facing east/west. Such arrays then spread peak power production across a few more hours a day. But the potential to spread power production across more hours is greater with wind power than with solar and will remain so for the foreseeable future.

[35] This progress is sometimes also correctly presented as wind turbines being productive in less windy areas, which is also the case; these turbines make do with less wind. But they also provide a smoother profile when installed in windy areas. See: https://energy.gov/eere/articles/unlocking-our-nation-s-wind-potential.

5. Narratives of social goals in climate discourse

In studies proposing nuclear as a solution to mitigate climate change, one rarely finds an admission that massive new builds would be needed. By 2050, the reactors completed around 1980 (almost all of those in North America and Europe, for instance) would be roughly 70 years old. The average age of the French nuclear fleet will surpass 40 by 2025. The oldest technically still operating reactor in the world, Beznau 1 in Switzerland, is 48 years old (commissioned on 1 September 1969), but it has been offline since March 2015, when microfissures were discovered in the containment vessel. In addition, indentions considered "not relevant for safety" were reported in August 2017; they had previously been discovered in the pressure chamber but not made public (SRF 2017).

If all the aging reactors online today worldwide were replaced by 2050, more than 400 would need to be added – around one per month from 2018-2050. And even then, nuclear only made up 2.3% of global final energy demand in 2015. If one reactor per week were added, the share could be quadrupled to around 10% if energy demand stagnated at the level of 2015, assuming current reactor size and capacity factors remain constant. Reaching 70% would require a new reactor every day. How likely is any of that?

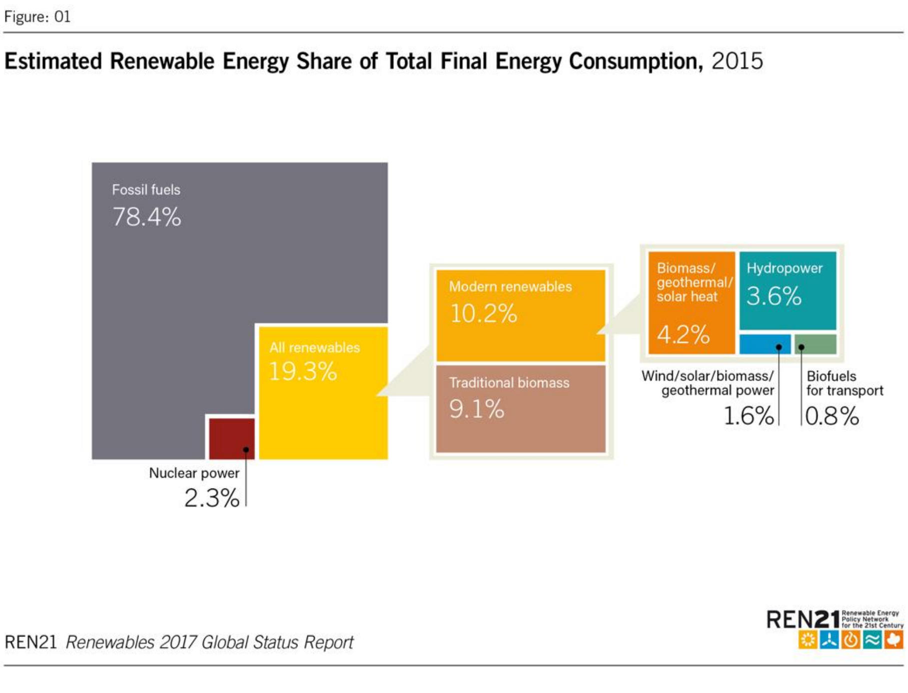


Figure 27: Shares of final energy consumption worldwide in 2015. Copyright: Renewable Energy Policy Network for the 21st Century.

Critics of renewables often claim that wind and solar energy cannot grow quickly enough (Smil 2013). There is no doubt that green energy is not currently growing fast enough to replace fossil fuels. One of the main findings in IRENA's REmap 2030 report is that renewables are only growing in line with energy demand and are therefore unable to offset fossil fuel consumption significantly (IRENA 2016). What nuclear supporters fail to mention, however, is that nuclear is falling behind. Its share of final energy dropped from 2.6% in 2012 to 2.3% in 2015 according to REN21's Global Status Report.

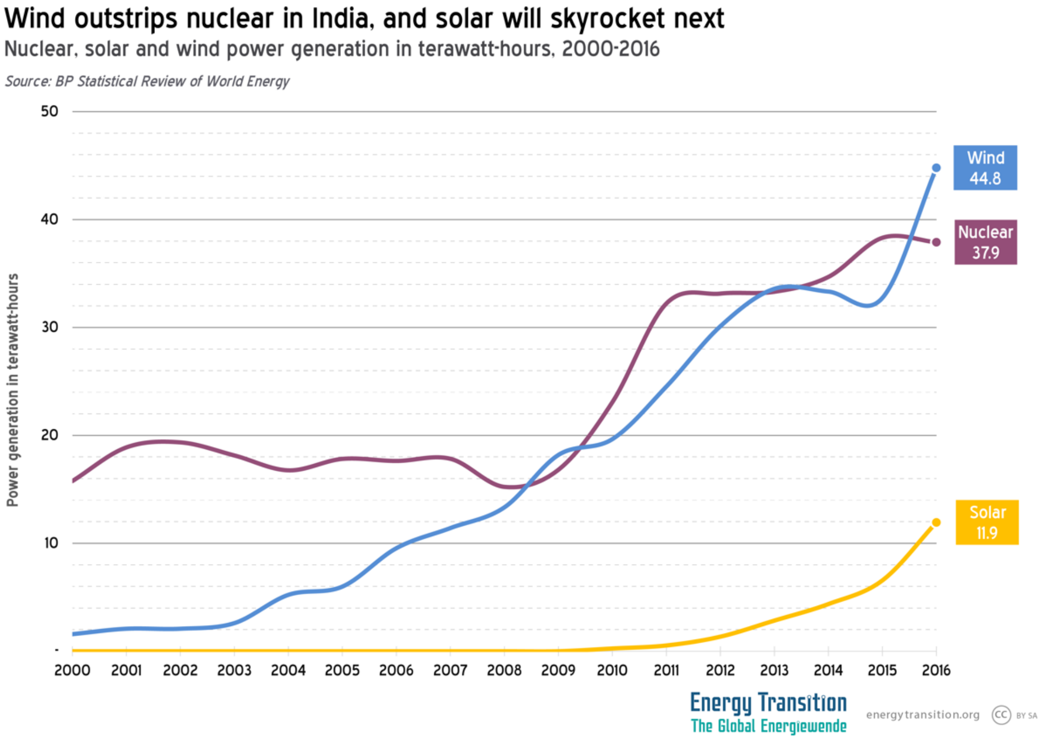


Figure 28: Nuclear, solar and wind power generation in India in TWh. Source: EnergyTransition.org. CC BY SA.

Areva, the French nuclear reactor manufacturer, has only sold three reactors abroad since problems at Civaux 1 were detected in 1998. One reactor was sold in Finland (Olkiluoto 3) in Finland. Two are going up in China (Taishan 1 & 2). At home, only one reactor in Flamanville is under construction. All four EPRs are far behind schedule and over budget.

The European Union investigated Civaux 1, the precursor to the EPR design, after "cyclic thermal loads" led to material fatigue, causing cracks in the heat removal system (Radu 2007, Felix 2016). The new reactor was still being tested when the damage was discovered (WISE 1998). It was supposed to be a flexible reactor for the future; instead, it seems to have undercut international confidence in French nuclear expertise. The failure of the EPR design to materialize hasn't helped either.

Extending the lives of existing reactors may make current nuclear plants uncompetitive. For France, it has been estimated that extensions from 40 to 50 years would require a purchase price of €55/MWh, far above the wholesale rates of around €35/MWh in 2017 (Mostue 2017).

In the US, the situation is no better. In 2017, the two reactors at Vogtle seemed likely to be abandoned along with another two at Sumner (Tomlinson 2017). These projects were canceled for financial reasons, not because there were any public protests against the technology.

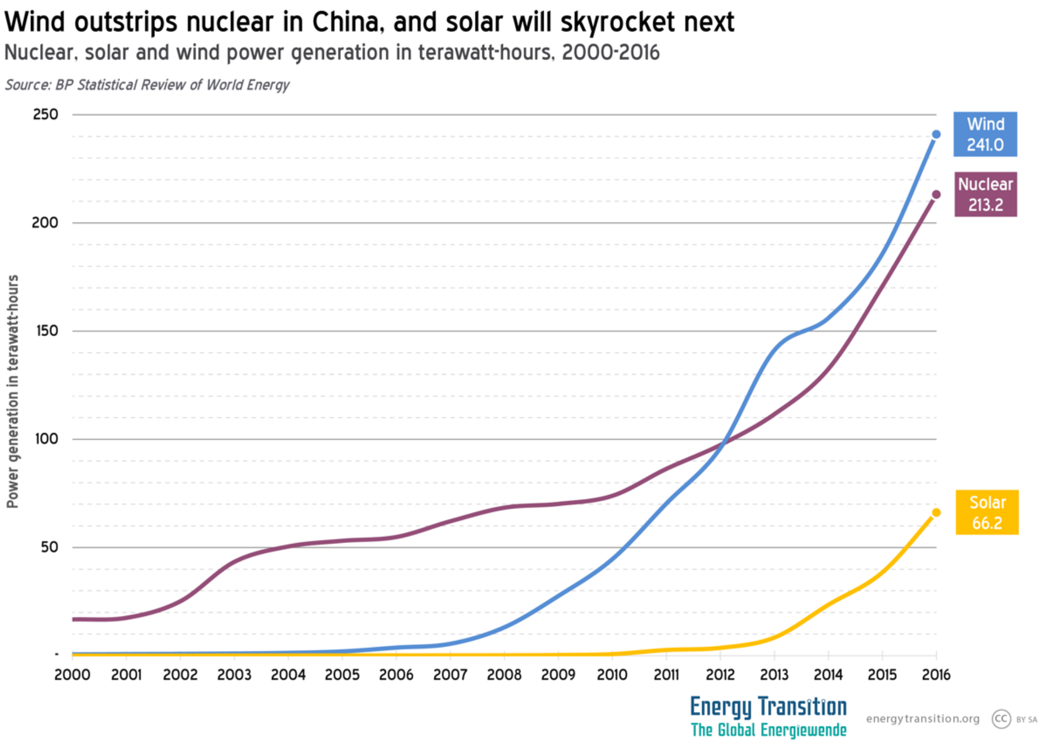


Figure 29: Nuclear, solar and wind power generation in China in TWh. Source: EnergyTransition.org. CC BY SA.

Indeed, even countries in the developing world that have long had ambitious plans for nuclear, such as India and China, are finding it easier to add kilowatt-hours from wind power than from nuclear. Solar power is also likely to skyrocket in these countries in a similar fashion, overtaking nuclear next decade.

Admittedly, not all issues have been resolved for deep decarbonization with wind and solar. It remains to be seen, for instance, whether the significant amount of demand shifting and storage will be available affordably for a power supply to be based largely on fluctuating renewables. On the other hand, significant progress – even beyond everyone's expectations – has been made in the past decade with wind, solar, and battery storage. In contrast, nuclear seems to be stalled in terms of cost and further technology development. Increasingly, those calling for nuclear seem to be less realistic than those calling for wind, solar and storage.

Proponents of nuclear need to address these real-world obstacles to nuclear power if the technology is to be part of the mitigation toolkit. Instead, we often see a rather unconvincing claim that low cost is the only thing that matters. Even if new nuclear builds prove to be less expensive than (partly stored) solar and wind – hardly a foregone conclusion – solely calling for low cost is too simplistic. (Brick and Thernstrom 2016), who critique Germany's Energiewende and call for more nuclear power, put it this way: "Electricity, as an input to most every single good and service in the world, should be as inexpensive as possible, and not a vehicle for pursuit of tangential social goals."

This argument is unlikely to sway anyone who sees a wide range of cobenefits from renewables. Indeed, it even fails to convince people who are open to nuclear power. One American journalist (Roberts 2017a) who argued that we should "keep nuclear power plants open as long as possible" and include nuclear designs in R&D later argued (Roberts 2017c): "There's no reason in the world to keep coal plants open and only one reason to keep nuclear plants open — climate change." Likewise, US energy consultant Hal Harvey, who has called for R&D into new reactor designs (Kokalitcheva 2016), has also stated that "the proper role for a nuclear advocate is being a genuine problem-solver, rather than a one-note advocate." (Harvey 2017)

One doesn't even have to list potential risks from nuclear waste or meltdowns to show why people prefer renewables to nuclear. There is concern, for instance, about the new Hinkley EPRs needing to be built at any cost in order to keep a nuclear supply chain in the country for security reasons (Johnstone 2015). The lowest price need not necessarily be the public's goal either; it seems that people from Australia to North America and Europe want to take advantage of the distributed nature of wind and solar to make their own energy, thereby overcoming the monopolistic market structures that have characterized the power sector since the beginning. Creating local economic value in rural areas is a main driver of renewables. As a German researcher critical of the sole focus on low cost recently put it, deep decarbonization models "assume that society will always seek to minimise costs, ignoring the potential role of personal preferences." (Creutzig 2017)

To put a finer point on this issue, it is unlikely that citizens will accept being told they cannot put solar on their roof or build a community wind farm just because a utility can provide the electricity for 0.5 cents less. In rural and small-town America – places falling behind during globalization – people are not saying, "Walmart is too expensive." They are saying: "the only thing here is Walmart." People want job opportunities and vibrant communities, which distributed renewable energy projects can be a part of. Proponents of nuclear would be well advised not to downplay these genuine desires, but to address them.

6. Conclusions

1. The cost of a future low-carbon power supply in 2050 depends on many factors: assumptions about future equipment costs decades hence, carbon prices, discounts rates, etc. But in all cases, the main cost driver will be the amount of power that cannot be consumed directly. Curtailment & storage must be kept to a minimum. The much touted “balanced mix” of nuclear along with wind and solar drives up the amount of C&S. This mix will thus be more expensive than a supply based primarily on nuclear (with little solar and wind) or based on solar and wind (with no nuclear).

2. Studies arguing that a significant share of nuclear mixed in with wind and solar rarely take account of the impact of lower capacity factors (capacity factors). The most common mistake is calculating the cost of nuclear merely based on capital costs without adjusting for capacity factors in screening curves.

3. No nuclear fleet has ever ramped in practice by significantly more than a third. Most pro-nuclear analysts argue that reactors could but don’t have to because nuclear plants have the lowest marginal costs and are therefore left running for economic reasons. However, reactors have never responded by more than a third even to extremely negative prices in Germany (which allegedly has the most flexible fleet worldwide along with France) of around -200 €/MWh.

4. When the German and French nuclear fleets ramp, they display unusual behavior. Instead of all units ramping at roughly similar levels (say, by 30%), as coal and gas fleets do, as few individual reactors as possible throttle output to the maximum so that as many reactors as possible can leave output as unchanged as possible. If nuclear fleets start ramping more to accommodate growing shares of wind and solar, this unique behavior could have impacts on grid stability, which have yet to be investigated as this unique ramping pattern does not seem to have been previously noticed.

5. Most studies investigating the inherent conflict between nuclear and fluctuating renewables have focused on wind power because solar power was still relatively insignificant. But solar clashes with nuclear more than wind does – a fact that future research needs to address more. Wind power generation is spread out across the day. In contrast, almost all solar power generation occurs within six hours (from 9 am to 3 pm). A mere ten percent share of solar power in countries like Germany, with low seasonal power demand in the summer, will thus squeeze out baseload plants entirely – or the solar power will need to be curtailed or storage. In contrast, Germany already has 13% wind power without any need for C&S.

6. In Germany, easy-to-understand visualizations of data were made publically available during the debate ten years ago. Today, multiple German websites allow the interested public to customize data visualizations of power sector data to an extent unknown in the United States. Much of the data that interested German laypeople play with online is proprietary in the US. Americans are comparatively shut out of the energy discussion.

7. The Germans have known about the Systemkonflikt between nuclear and wind & solar for a decade. The result is an informed, open discussion between experts and laypeople

in which even the diction used is more precise. Flexibility options (Flexibilitätsoptionen) are needed, not just baseload or dispatchable power. The English-speaking world continues to debate what "dispatchable" means, whether wind and solar are "intermittent" or "variable", and whether baseload is a bug or feature. The German debate knows no such confusion. Gas turbines are quickly dispatchable; inflexible baseload is not. And inflexible baseload is incompatible with fluctuating wind and solar.

8. Renewables can grow quickly enough to replace nuclear; coal will not be needed. Claims about nuclear being necessary towards "deep decarbonization" are often based on misunderstandings about Germany, specifically claims that Germany has needed coal to replace nuclear. In fact, Germany replaced the power from the eight reactors closed in 2011 with new renewables in only three years and had less coal power in 2016 than in 2010.

9. Calls for a large share of nuclear also rarely explain how unlikely massive new builds are. Though not sufficient up to now, the growth of renewables is at least accelerating. Nuclear is falling behind.

10. All talk of nuclear as a possible "friend" of wind and solar or as a "bridge technology" stems from a wish to make everyone happy. This approach overlooks technical conflicts but fits the US energy policy of "all-of-the-above." Germany has moved beyond such political compromises and accepts physical realities in energy policy. The Energiewende identifies enemies: if significant shares of fluctuating wind and solar are the goal, inflexible baseload must go, and nuclear is the least flexible source of baseload power.

Three options are commonly proposed for deep decarbonization:

1. a reliance on nuclear;

2. a reliance on wind and solar; and

3. a mix of nuclear with wind and solar.

As France shows, we can have deep decarbonization based largely on nuclear. No country yet proves that the second combination – wind and solar – will work, but all signs indicate that such scenarios are becoming more feasible by the year – while nuclear becomes increasingly irrelevant, even in France.

The third option – the much touted "balanced" mix of nuclear with wind and solar – is a chimera. No country will ever demonstrate that nuclear is a good complement for wind and solar unless some future reactor design ramps like current gas turbines at a competitive price.

Germany is widely criticized for abandoning its experiment to mix wind, solar and nuclear in 2011. But such critics incorrectly assume that this mix will work. France is now poised to conduct its own experiment, and it is unlikely to go well. The real threat to the dream of a balanced mix of nuclear, wind and solar is thus not Germany's Energiewende, but the French transition énergétique.

Can reactors react? This paper finds that nuclear reactors cannot to the extent needed for a significant share of wind and solar. Nuclear, or wind and solar? We have to choose.

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8. About the author

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Born in the US, Craig Morris (@PPchef) has lived in Germany since 1992 and worked in the energy sector since 2001. He is currently a Senior Fellow at the Institute for Advanced Sustainability Studies in Potsdam, Germany, and is the co-author of *Energy Democracy*, a history of Germany's Energiewende (energy transition) as a grassroots movement (Palgrave 2016). He has served as technical editor of both editions of IRENA's REmap since 2013 and of the 2015 edition of Greenpeace's Energy (R)evolution. In 2008, he cofounded Berlin's PV Magazine; in 2010, Renewables International. In 2012, he became lead author of EnergyTransition.com. Since 2002, he has also authored articles and books in German and served as editor for numerous German periodicals in the energy sector. In 2014, he won the International Association of Energy Economists' prize for energy journalism.

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