Is Wind the Next Nuclear?

What the nuclear stagnation tells us about the challenges that lie ahead for renewable energy

Schalk Cloete

Introduction Levelized costs of electricity often dominate the energy and climate debate. Green advocates like to believe that if we only invest enough in wind and solar, the resulting cost reductions will soon put an end to fossil fuels. While this is already a strongly oversimplified viewpoint, a narrow focus on cost makes such simplistic analyses even less helpful.

This article will elaborate by example of two clean energy technologies that face very different non-economic barriers: nuclear and wind.

The Nuclear Stagnation

When technology is new and exciting, people only see the positives. It is only when we reach market shares where people start experiencing negative impacts that opinions turn negative.

In the case of nuclear, the global expansion was handicapped by the Chernobyl disaster in 1986, and the nascent developing world expansion was interrupted by Fukushima in 2011. As shown in **Figure 1**, Chernobyl happened when nuclear reached about 5 % of the global energy supply. Today, we are back down to 4.2 %.

Deaths from Chernobyl are estimated somewhere between 4,000 and 60,000[1], only 31 of which can be attributed directly to the blast and high-level radiation exposure. Fukushima had a much lower death toll at 574[2], almost all due to evacuation stress. For perspective, it is estimated that one future premature death results from every 300 to 3000 tons of burnt carbon[3] or 1100 to 11,000 tons of CO_2 released into the atmosphere. Hence, if we assume that the 93,000 TWh of nuclear power generated to date displaced coal at 0.8 ton-CO_2/MWh, the 74 billion tons of CO_2 avoided by nuclear has already saved 7–70 million lives, not counting the additional impact of avoided air pollution.

There is much controversy around these estimates, but they serve to illustrate that the public health benefits of nuclear easily outweigh the costs. Clearly, the public backlash against nuclear was not rational from a big-picture view. But that does not matter. The effects of public resistance are real, whether it is rational or not.

A Wind Stagnation?

As **Figure 1** shows, wind market share is currently expanding at about half the speed of nuclear market share in the seventies and eighties. Although wind does not face risks from black swan events[4] like nuclear, it faces its own brand of public resistance, both to the turbines themselves and the extensive network expansions required to integrate higher wind shares.

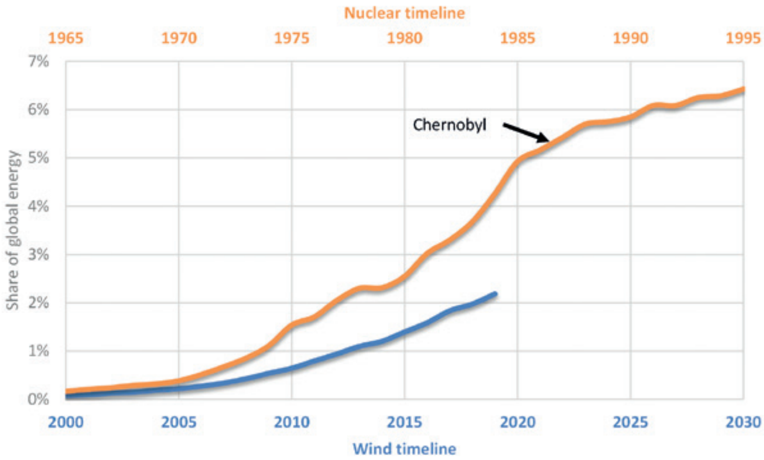

Fig. 1.
Comparison of the global expansion of wind and nuclear from BP Statistical Review data. Both wind and nuclear electricity output are multiplied by 2.5 to convert it to displaced primary fossil energy. Source: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

As our societies become more advanced, we increasingly demand an invisible energy system. Over here in Norway, the usually reserved population is reacting furiously[5] to onshore wind expansion plans. Turbines dotting the pristine Norwegian landscape are unimaginable to this wealthy society, the origin of its wealth[6] notwithstanding. In Germany, resistance to turbines and grid expansions has almost brought onshore wind expansion to a halt[7] at current levels (about 7 % of total energy demand).

That is wind's greatest challenge: It is the most visible energy technology we have. As wind power continues to expand and turbines grow ever larger, its visibility will only grow while society's tolerance for highly visible energy technologies continues to decline. Advanced societies also become increasingly concerned with nature preservation, leading to additional hurdles related to bird protection[8].

Offshore wind can help, but it will need to be built far from shore to be sufficiently invisible, making it more costly. It also faces further economic challenges from wake effects that strongly reduce output[9] as total installed capacity increases. In addition, offshore wind requires large grid expansions to serve inland regions. Making

1 https://ourworldindata.org/what-was-the-death-toll-from-chernobyl-and-fukushima
2 https://ourworldindata.org/what-was-the-death-toll-from-chernobyl-and-fukushima
3 https://www.frontiersin.org/articles/10.3389/fpsyg.2019.02323/full
4 https://en.wikipedia.org/wiki/Black_swan_theory
5 https://www.worldoil.com/news/2020/12/9/more-norwegians-saying-not-in-my-backyard-to-onshore-wind-farms
6 https://edition.cnn.com/2021/02/17/world/climate-hypocrites-uk-canada-norway-intl/index.html
7 https://www.dw.com/en/german-wind-energy-stalls-amid-public-resistance-and-regulatory-hurdles/a-50280676
8 https://www.cleanenergywire.org/news/german-environment-ministry-weighing-wind-farm-distance-regulations-protect-birds
9 https://www.agora-energiewende.de/en/publications/making-the-most-of-offshore-wind

these expansions invisible (underground cables) is very expensive.

Solar is not immune either. Large solar farms can ruin scenic vistas and damage natural habitats. Waste from decommissioned plants could be another major concern.[10] Furthermore, transmitting solar energy from sunny regions to population centers (often poorly correlated[11]) will face similar resistance to wind network expansions. Ultimately, any industrial-scale energy technology has its drawbacks, and variable renewables are no exception[12].

Like nuclear, most of the resistance to renewables is not rational from a big-picture viewpoint. Surely, seeing the occasional wind turbine in the wild is worth the climate benefits. But again, the rationality of this resistance does not matter. What matters is the effect it has on clean technology deployment.

The Undervalued Issue of System Complexity

Megaprojects that involve many interconnected technical, economic, political, and social challenges are extremely difficult to execute on time and within budget. Nuclear offers a prime example with many stories of budgets and timelines that were grossly exceeded, increasingly stringent safety regulations being only one reason[13].

In comparison, the modular construction and installation of a wind turbine is child's play. For decades, the simple and standardized construction and installation of wind and solar have been a big driver behind their impressive growth and falling costs.

But this will not last. Higher wind market shares require vast grid expansions (often into neighboring countries) and lots of integration with other sectors that previously operated independently (and need to be reinvented to run on clean energy). In the longer term, this includes a large hydrogen production, transport, storage, and end-use sector that must be built from scratch. Executing this enormous integrated project in a shifting policy-technology landscape with impossibly tight climate timelines and increasing public resistance can easily surpass the scale and complexity of nuclear projects.

As the nuclear example shows, sub-optimal execution should be expected in such a large, complex, and multi-faceted project, inflating overall system costs and slowing the energy transition.

The remainder of this article will quantify these effects using a modified version of a published energy systems model[14] loosely based on Germany (further model details are given in the Appendix).

Model Results

The coupled electricity-hydrogen system model is run for three distinct scenarios, each varying the most relevant model parameter:

- **No CCS or Nuclear:** In this renewables-dominated scenario, the critical variable is the added costs from integration challenges, public resistance, and high system complexity. These costs are varied via cases that double and triple the added electricity and hydrogen grid costs needed to connect wind and solar generators to demand centers.
- **No CCS:** This scenario allows nuclear but not CO_2 capture and storage (CCS). The critical variable in this scenario is the cost of constructing nuclear power plants, varied between 4000 and 8000 €/kW.
- **All Technologies:** CCS is allowed to decarbonize natural gas-fired power and hydrogen production. The natural gas export price is the critical variable in this

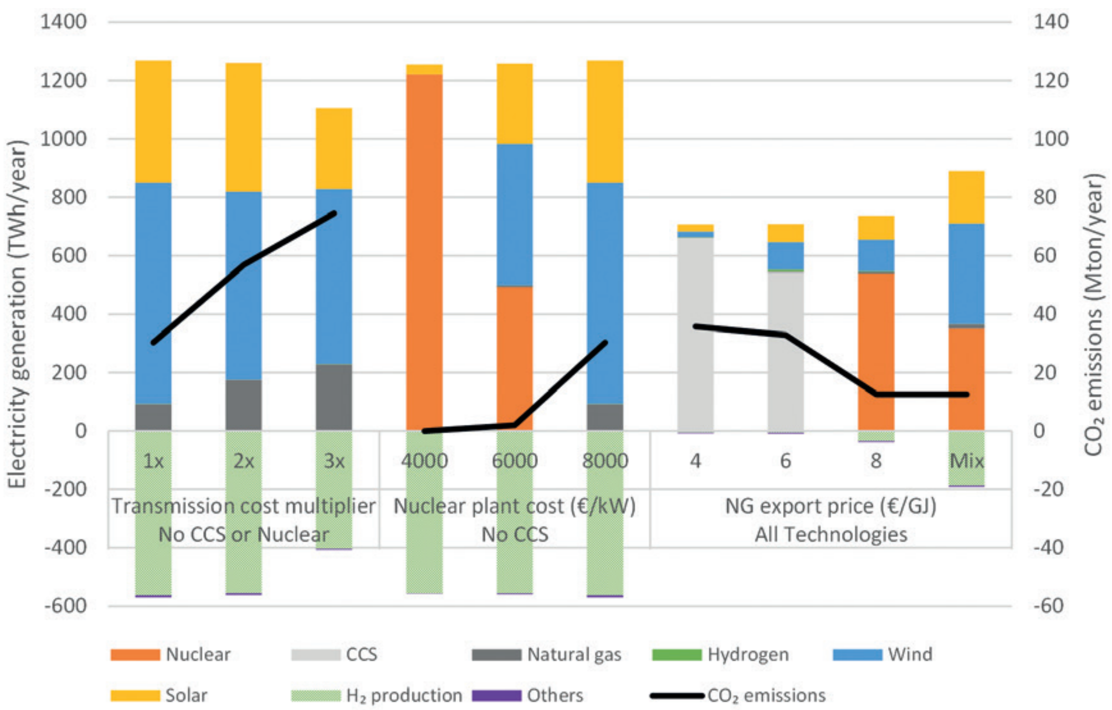

Fig. 2.
Optimal electricity generation and consumption in the different cases. CCS = Natural gas power production with CO_2 capture and storage; Natural gas = Unabated natural gas power production; Others = Efficiency losses from batteries and electricity consumption involved in hydrogen storage.

10 https://hbr.org/2021/06/the-dark-side-of-solar-power
11 https://energycentral.com/c/ec/what-potential-distributed-generation
12 https://www.brookings.edu/wp-content/uploads/2020/01/FP_20200113_renewables_land_use_local_opposition_gross.pdf
13 https://arstechnica.com/science/2020/11/why-are-nuclear-plants-so-expensive-safetys-only-part-of-the-story/
14 https://www.sciencedirect.com/science/article/pii/S0360319920336673?via%3Dihub

scenario and is varied between 4 and 8 €/GJ (natural gas transmission costs are added separately).

In addition, a **Mix** case is added where a balanced mix of renewables, nuclear, and natural gas with CCS is deployed. This case shows the potential of deploying renewables and nuclear up to the point where public resistance and complexity become limiting, and deploying a limited amount of natural gas where it adds the most value, i.e., hydrogen production and system balancing.

In each scenario, the model optimizes investment and hourly dispatch of all the technologies listed in the Appendix to minimize total system costs. The default settings of the three critical variables in the scenarios are 1) no increase in grid costs, 2) 6000 €/kW nuclear capital cost, and 3) 6 €/GJ natural gas export price. A high CO_2 price of 200 €/ton is assumed in all cases.

The Electricity Mix

Electricity production and consumption from the optimal technology mixes for different cases are shown in **Figure 2**. Starting from the **No CCS or Nuclear** scenario on the left, we see that higher transmission costs reduce the deployment of renewables and increases CO_2 emissions from unabated natural gas-fired power production. With the base grid costs (1x) derived from a Berkeley Lab study[15], all required hydrogen is made locally using electrolysis. However, this scenario requires 267 GW of installed wind capacity (two-thirds onshore) – quadruple the current installed base in Germany, where public resistance already has a large negative impact on wind expansion plans. In addition, 378 GW of solar power is needed (7x the current level).

When transmission costs are tripled – a likely scenario given the public resistance and complexity anticipated from such vast wind and solar deployment – a considerable amount of unabated natural gas-fired power production is deployed. Even with a CO_2 price of 200 €/ton, higher renewable energy integration costs preserve a central role for unabated natural gas in the power system. In addition, this case relies on expensive hydrogen imports via green ammonia for 28 % of the hydrogen demand.

The inclusion of nuclear in the **No CCS** scenario creates a near 100 % nuclear system when projects are well executed to build plants for 4000 €/kW. According to the latest power plant cost database from the IEA and NEA[16], nuclear plants have investment costs ranging from 2300 €/kW in Korea to 4500 €/kW in the United States, so such costs are feasible. Even at the baseline cost of 6000 €/kW, nuclear maintains a central role in the power system. However, at 8000 €/kW (e.g., the Hinkley Point C[17] project), costs become excessive, and the optimal solution is the same as the base case (1x) in the **No CCS or Nuclear** scenario.

When CCS is allowed in the **All Technologies** scenario, natural gas-fired power plants with CCS become the favored technologies at natural gas export prices of 6 €/GJ and lower. Renewable energy deployment is low because CCS (and nuclear) plants are best operated as baseload generators and natural gas is used for all hydrogen production, removing the possibility of electrolysis to balance fluctuating wind and solar output. The natural gas price of the base case (6 €/GJ + transmission) is a little

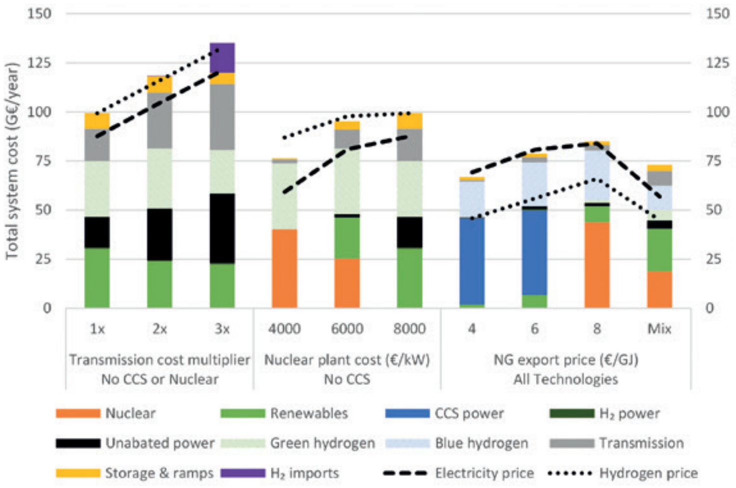

Fig. 3.
Optimized costs of the energy system in the different cases. The cost of generating clean electricity for green hydrogen production (either from renewables or nuclear) is included directly in green hydrogen costs.

higher than long-term European natural gas prices projected in the IEA Stated Policies Scenario in the latest IEA World Energy Outlook[18] and implies large profit margins for natural gas producers. The IEA's Paris-compatible Sustainable Development Scenario projects natural gas prices below the 4 €/GJ level due to reduced demand.

When CCS is available, steam methane reforming of natural gas is used for almost all hydrogen production, strongly reducing the amount of extra electricity production needed for electrolysis. Natural gas is only driven out of the power sector when prices rise to 8 €/GJ, displaced mainly by nuclear. However, it remains responsible for 94 % of hydrogen production, even at this high price level.

Finally, the **Mix** case shows the result when wind and solar power are forced to levels likely to prevent excessive public resistance and system complexity: 80 GW of onshore wind, 40 GW of offshore wind, and 160 GW of solar. This case also assumes an efficient nuclear rollout at 4000 €/kW and low natural gas prices of 4 €/GJ due to reduced demand. One-third of hydrogen comes from electrolysis in this case, which plays a central role in balancing renewables while nuclear provides baseload power (see **Figure 4** in the Appendix).

Total System Costs

The minimized annual system costs of the different cases are shown in **Figure 3**. For the **No CCS or Nuclear** scenario, the high costs of unabated natural gas-fired power production (mainly from the high CO_2 price) are clearly visible. However, this costly generation remains the cheapest way to supply power during extended periods of low wind and solar output. In addition, significant transmission, storage, and ramping costs are shown. When transmission costs are tripled (the 3x case), the model chooses to deploy considerably fewer renewables to reduce this high integration cost, resulting in much higher costs from unabated natural gas power plants and hydrogen imports.

15 https://www.sciencedirect.com/science/article/abs/pii/S0301421519305816?via%3Dihub
16 https://www.oecd-ilibrary.org/energy/projected-costs-of-generating-electricity_20798393
17 https://en.wikipedia.org/wiki/Hinkley_Point_C_nuclear_power_station
18 https://www.oecd-ilibrary.org/energy/world-energy-outlook-2020_557a761b-en

When nuclear plants can be built for 4000 €/kW in the **No CCS** scenario, energy system costs reduce substantially. This case requires no natural gas power production and almost no added transmission, storage, and ramping costs. Nuclear plants operate at baseload conditions with electrolyzers used to balance daily demand variations, leading to an attractively simple energy system. Increasing the cost of nuclear to 6000 €/kW brings more wind and solar into the system with the associated balancing costs. If nuclear costs escalate to 8000 €/kW, nuclear is too expensive, and the system reverts to the 1x case in the **No CCS or Nuclear** scenario (as shown in **Figure 2**).

The addition of CCS in the **All Technologies** scenario brings further cost reductions, especially with a natural gas export price of 4 €/GJ. The main benefit of including CCS is that hydrogen becomes much cheaper. However, a system that is so dependent on natural gas is undesirable, and substantially higher shares of renewables and nuclear would be preferred from the perspective of energy security and long-term sustainability. Natural gas export prices need to rise to unrealistic values of 8 €/GJ before nuclear (at 6000 €/kW) displaces natural gas power plants with CCS.

Finally, the **Mix** case illustrates how these three technology classes (renewables, nuclear, and CCS) can be combined to create a cost-effective system that avoids the challenges from over-reliance on any single technology class. Renewables and nuclear are deployed to levels where complexity and public resistance are deemed manageable, allowing for optimistic assumptions (no grid cost escalations and 4000 €/kW nuclear), while natural gas demand is minimized, making a low export price of 4 €/GJ seem reasonable. As shown in **Figure 3**, this case with 401 TWh/year of natural gas demand is only 10 % more expensive than the cheapest case that demands an unrealistic 1743 TWh/year of natural gas.

Conclusions

An over-reliance on any energy technology class can be detrimental, creating a range of social, political, and environmental challenges. As discussed in this article, the hurdles facing wind and nuclear are very different, but both are highly significant. As wind power continues to expand to the level where nuclear peaked (it is currently about one-third of the way there), public resistance and system complexity will continue to mount, causing substantial headwinds.

Ultimately, wind and solar will follow the same S-curve deployment pattern[19] of all other energy technologies, but the plateau may well come earlier than proponents believe. For this reason, nuclear and CCS should be encouraged for parallel deployment, especially in regions with poorer wind/solar resources or high population densities. The ability to construct these energy-dense technologies close to demand and dispatch them as needed results in a much simpler and less obtrusive energy system.

An all-of-the-above approach to the energy transition guided by technology-neutral policies remains the rational choice. Each technology class has its limits and weaknesses, and we need a balanced mix to allow each technology to do what it does best. Cheap wind and solar are great at moderate deployment levels, but other clean technologies will be needed to reach net-zero. Nuclear is one of these options, while CCS has a vital role to play in system balancing and clean fuel provision.

The global energy transition is a clean energy team effort. All the players deserve our support.

Appendix: Model Description

A modified version of the energy system model discussed in a previous article[20] is used in this study to illustrate the large effects of renewable energy and nuclear cost inflation caused by the range of techno-socio-economic factors

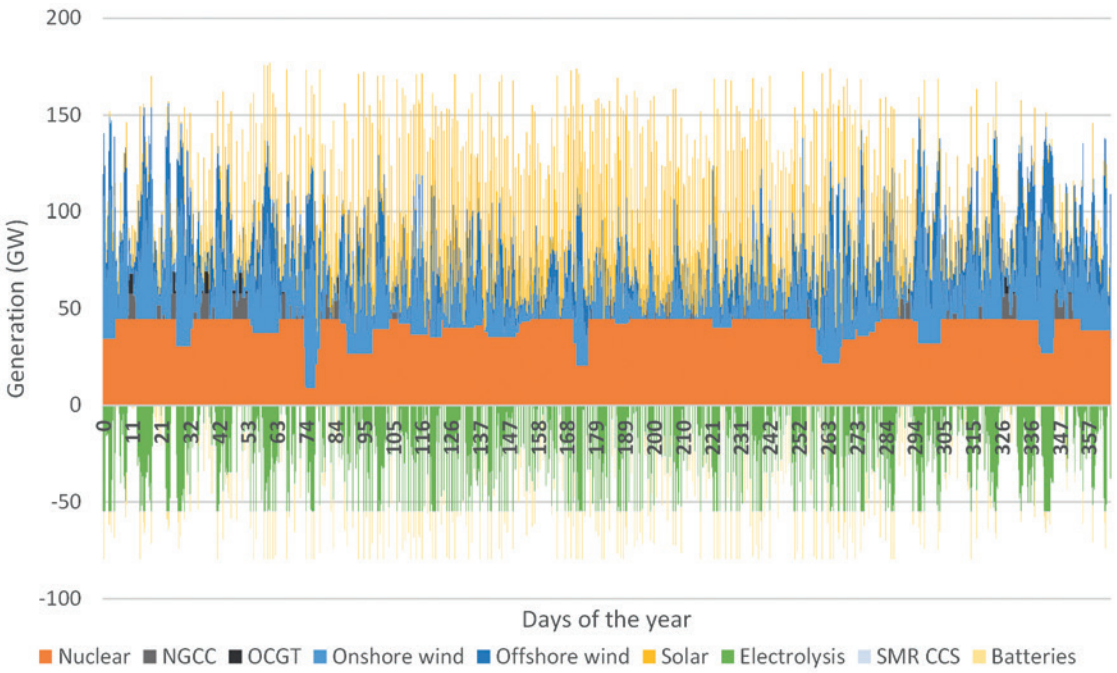

Fig. 4.
Hourly electricity generation profile for the "Mix" case. Electricity consumption (mainly electrolyzers and battery charging) is shown as negative generation. NGCC = Natural gas combined cycle; OCGT = Open cycle gas turbine; SMR CCS = Steam methane reforming with CO2 capture and storage.

19 https://extrudesign.com/what-is-technology-s-curve
20 https://energypost.eu/green-or-blue-hydrogen-cost-analysis-uncovers-which-is-best-for-the-hydrogen-economy/

discussed above. The model is loosely based on Germany and is designed to optimize investment and hourly dispatch of a range of technologies, including:

- **Nine different electricity generators:** onshore and offshore wind, solar PV, nuclear, natural gas combined-cycle plants with and without CCS, open cycle gas turbine peaker plants, hydrogen combined and open-cycle plants
- **Lithium-ion batteries** for electricity storage
- **Two clean hydrogen generators:** steam methane reforming with CCS (blue hydrogen) and electrolysis (green hydrogen)
- **Two hydrogen storage technologies:** cheap salt caverns with slow charge/discharge rates and locational constraints and more expensive storage tanks without such limits
- **Hydrogen can also be imported in the form of green ammonia** that is reconverted to hydrogen in reconversion plants included in the model

In addition, transmission costs for electricity, hydrogen, natural gas, and CO_2 are included in the model.

- **Electricity transmission** is included only for wind and solar generators, accounting for the distance between demand centers and high-quality resources in publicly accepted regions. The base case assumes 300, 500, and 200 €/kW of added grid costs for onshore wind, offshore wind, and solar PV, respectively.
- **Hydrogen and natural gas transmission** costs are included for hydrogen- and natural gas-fired power plants and steam methane reforming plants. Despite natural gas pipelines being cheaper than hydrogen pipelines, natural gas pipeline costs are set to 200 €/kW relative to 150 €/kW for hydrogen because natural gas needs to be imported from abroad, whereas hydrogen is only transmitted locally between producers and consumers.
- **Hydrogen transmission** costs to locationally constrained salt caverns are also included. These costs are assumed to escalate from 100 to 500 €/kW as capacity increases, accounting for the fact that intermittently operated electrolyzers co-located with wind and solar (see next point) will first exploit sites close to salt caverns before more distant sites need to be used.
- **Electrolyzers are assumed to be co-located with wind and solar plants** to avoid the electricity transmission costs mentioned in the first point. These electrolyzers are assumed to avoid transmission capacity costing 300 €/kW in exchange for added hydrogen transmission costs of 150 €/kW. Since electrolyzers consume more electricity than they produce hydrogen, the net saving is about 200 €/kW of transmission capacity – a substantial benefit.
- **CO_2 transport and storage** infrastructure costs are added to CCS power and hydrogen plants. High costs are assumed, given the high resistance to CCS in Germany, amounting to levelized costs of 23 €/ton when CCS plants are operated at the maximum allowable capacity factor of 90 % (costs escalate with lower capacity factors).

In the **No CCS or Nuclear** scenario, the electricity, hydrogen, and natural gas transmission costs are increased to 2x and 3x the default levels to account for the following factors:

- The need to build turbines in more isolated sites or far offshore to satisfy local stakeholders
- Avoiding public resistance to grid expansions via expensive underground transmission lines
- Having to resort to sites with lower quality wind or solar resources
- Paying fees to local communities to allow construction closer to demand centers
- Potentially large end-of-life recycling and disposal costs of solar panels and turbine blades
- A sub-optimal buildout of the complex and highly interdependent systems required to integrate high shares of wind and solar

Costs related to ramping natural gas and nuclear power plants are also included, amounting to 20 % of the total annualized fixed cost in €/kW/year per MW of up or down ramp.

In all cases, total annual electricity demand is set to the fluctuating hourly profile observed for Germany in 2018, requiring a total of 499 TWh of production per year. In addition, flat demand for hydrogen of 400 TWh/year and additional electricity (increased electrification) of 200 TWh/year is included. This extra hydrogen and electric energy is equivalent to about a third of German non-power oil & gas consumption, implying that great efficiency advances and more clean energy deployment will be needed to reach net-zero emissions.

The GAMS software is used to minimize total system costs by optimizing the deployment and hourly dispatch of all production, transmission, and storage technologies. To keep computational costs reasonable, only every 7th hour is simulated. A previous sensitivity analysis[21] has shown that this assumption still yields accurate results.

As an illustration, hourly power production profiles for the balanced **Mix** case are shown in **Figure 4**. The good seasonal complementarity between wind and solar in Germany is clearly observed. Nuclear's baseload role is also illustrated with electrolyzers and batteries mainly responsible for balancing wind and solar power. Natural gas power plants run only during isolated instances of high demand and low renewable energy output.

Author

Schalk Cloete
Research Scientist
SINTEF
Trondheim, Norway
Schalk.Cloete@sintef.no

Schalk Cloete is a research scientist working on solutions to our great 21st-century sustainability challenge: give every world citizen a fair shot at a decent life without destroying the ecological carrying capacity of our planet. After reaching early financial freedom, he retired from the research rat race and is currently 40 % employed at the Norwegian research institute, SINTEF, where he develops novel clean energy conversion technologies. His free-time research is dedicated to policy and lifestyle design strategies for a rapid and just transition to a sustainable global society.

21 https://www.econstor.eu/handle/10419/234469