Availability and technical and economic feasibility of low-carbon alternatives to nuclear energy

Expert Statement, Dipl.-Phys. Oda Becker, Hannover, 17.04.2023

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1. Introduction

In recent years, strong growth in electricity generation from renewables has been observed worldwide and in the EU. Due to the growth of renewables, more and more fossil fuel-fired power plants are being shut down.

The capacity of nuclear power plants is decreasing because they are no longer economically viable and also because construction times are so long.

Nuclear power does not support the expansion of renewables, there is no practical or theoretical evidence for this hypothesis, but a number of scientific studies prove the opposite.

2. Nuclear is not needed to facilitate absorption of renewables

The Commission states that "far from hampering renewable energy sources, the presence of nuclear energy in the energy mix facilitates grid stability and thus higher absorption of renewable energy sources." As evidence for this statement, it is only one article quoted by the Commission: Daniel Perez: An attempt of reproduction of Sovacool et al.'s, 'Differences in carbon emissions reduction between countries pursuing renewable electricity versus nuclear power'. 2022. This article is a short paper from a mathematic PhD Student who does not work in the field of energy.

SOVACOOL et al. (2020) performed a study concluding that "the implication for electricity planning is that diverse renewables are generally proving in the real world to be significantly more effective than nuclear power at reducing climate disruption".

SOVACOOL et al. (2020) use multiple regression analyses on global datasets of national carbon emissions and renewable and nuclear electricity production across 123 countries over 25 years to examine systematically patterns in how countries variously using nuclear power and renewables contrastingly show higher or lower carbon emissions. They find that larger-scale national nuclear attachments do not tend to associate with significantly lower carbon emissions while renewables do. They also find a negative association between the scales of national nuclear and renewables attachments. This suggests nuclear and renewables attachments tend to crowd each other out.

PEREZ (2022) states that in attempting to reproduce the results of SOVACOOL et al. (2020), he found that the analysis performed was significantly compromised due to both errors in the statistical analysis and inconsistencies in the authors' logic. According to PEREZ (2022), these two points represent contradictions in logic:

- the "'crowding out" hypothesis, i.e. that renewables and nuclear are structurally incompatible, so that there is an anti-correlation between them;
- the rejection of the "climate change mitigation" hypothesis, which states that " the relative scale of national attachments to nuclear electricity production will vary negatively with carbon emissions ".

However, PEREZ (2022) did not provide any evidence or quotations that these issues are contradictions in logic. On the other hand, the crowding-out hypothesis that renewable energy and nuclear energy are structurally incompatible, so that there is an anti-correlation between them, is supported by the reality and mentioned by many scientists working in the energy field. **Even the energy utilities EON and EDF, which operate nuclear power plants, demanded that the share of renewable energies be limited. The reasoning behind this is as follows: Would RE not be limited artificially, large capacities would be taken over by RE as they are more competitive in every aspect than nuclear energy. Nuclear energy plants, in turn, can only operate in high loads, that cannot be absorbed, if RE are not limited. The conflict of flexible and non-flexible energy generation techniques becomes clear by this.**

Secondly, SOVACOOL´s intention in his extensive study was to evaluate the "climate change" hypothesis. PEREZ (2022) only complains that SOVACOOL et al. (2020) rejects the hypothesis, but provides no evidence that the hypothesis could be correct.

In order to assess the intention and meaning of the article, it is important to know that Daniel Perez is volunteering with the “Voices of Nuclear”.[1] The “Voices of Nuclear“ is a citizen association of volunteers, independent of any economic, institutional, union or political ties. The “**goal is to contribute to the recognition of nuclear energy as essential to the low carbon energy transition**.” According to his own declaration, Daniel Perez is "responsible for is responsible for advertising campaigns on Facebook, Twitter and LinkedIn” and “he developed several videos in 7 languages to popularise nuclear issues”.[2]

3. Feasibility of highly Renewable Scenarios

In the scientific magazine “Renewable and Sustainable Energy Reviews” a comprehensive article was recently published (BROWN et al. 2018). It was the answer to an article that called into question the feasibility of highly renewable scenarios. **BROWN et al. (2018) conclude that the 100% renewable energy scenarios proposed in the literature are not just feasible, but also viable**. **100% renewable systems that meet the energy needs of all citizens at all times are cost-competitive with fossil fuel-based systems, even before externalities such as global warming, water usage and environmental pollution are taken into account**.

The authors of "burden of proof..."claim that a 100% renewable world will require a ‘reinvention’ of the power system (HEARD et al. 2017). However, BROWN et al. (2018) have shown that this claim is exaggerated: only a directed evolution of the current system is required to guarantee affordability, reliability and sustainability.

A joint study by the Energy Watch Group and Lappeenranta University of Technology, Finland. simulates the global energy system based on 100% renewables across the sectors of electricity, heating, transport and desalination (RAM et al. 2019). While the full study is due in early 2019, a first part analysing the electricity sector was released already in December 2017. It shows that a transition to 100% renewables in the global electricity sector is technically feasible at every hour throughout the year and proves more cost-effective than the existing system, with the levelized cost of electricity from renewable sources (LCOE) expected to decline from €70/MWh in 2015 to €52/MWh by 2050 (including curtailment, storage and some grid costs). The study further demonstrates that the global transition to a 100% renewable electricity system would reduce power-related greenhouse gas emissions to zero by 2050 and create in total an estimated 36 million jobs in the electricity sector by 2050 in comparison to 19 million jobs in 2015. The study provides policy recommendations, which can lead to a full transition to 100% renewable electricity even before 2050, if they are successfully implemented. **Conclusion: Global energy-related greenhouse gas emissions can be reduced to zero by 2050, or sooner, across all energy sectors.**

According to a recent review on 100% renewable energy studies (HANSEN et al. 2019), currently there is no uniform definition of 100% renewable energy and the majority of studies on 100% renewable energy only focus on the power sector. Some of the 100% renewable energy studies propose a 100% renewable power system and electrify all energy sectors. For example, Jacobson et al. (2017) have proposed a 100% renewable energy system solely based on water, wind and solar for 139 countries in the world. This study concluded that meeting system-wide 100% renewable energy penetration with water, wind and solar is technically and economically feasible. (YUE et al. 2020)

[1] https://www.voicesofnuclear.org/

[2] https://www.math.ens.psl.eu/~perez/CVEnglish.pdf

The reality shows that 100% renewable energy supply is feasible, there are already 16 countries or US near 100% annual electricity generated or consumed from wind, water or solar (WWS) see Figure 1.

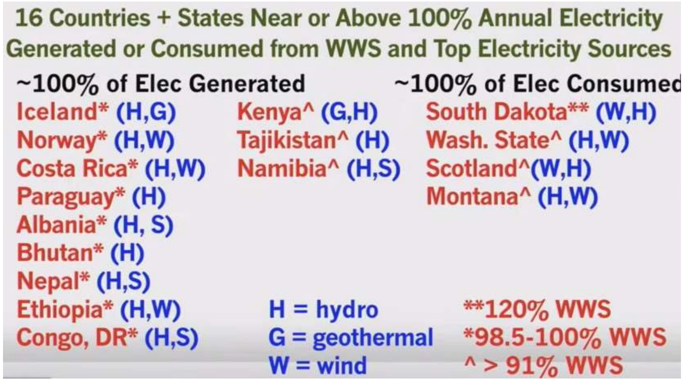


Figure 1: Countries or states near 100% annual electricity generated or consumed from wind, water or solar.

4. Global growths in electricity generation from renewables and decline in nuclear power.

The continuing fall in the construction costs of renewables means that there is still an even greater rise in the net annual increase in installed capacity when investment increases. In total, a record 314 GW of renewable energy capacity was installed in 2021, according to REN21, an increase of 17 percent over the addition in the previous year.[3]

The pace of wind power deployment has picked up again in 2021 with a net increase in global capacity of 92 GW, according to IRENA, leading to a global installed capacity of 823.5 GW.

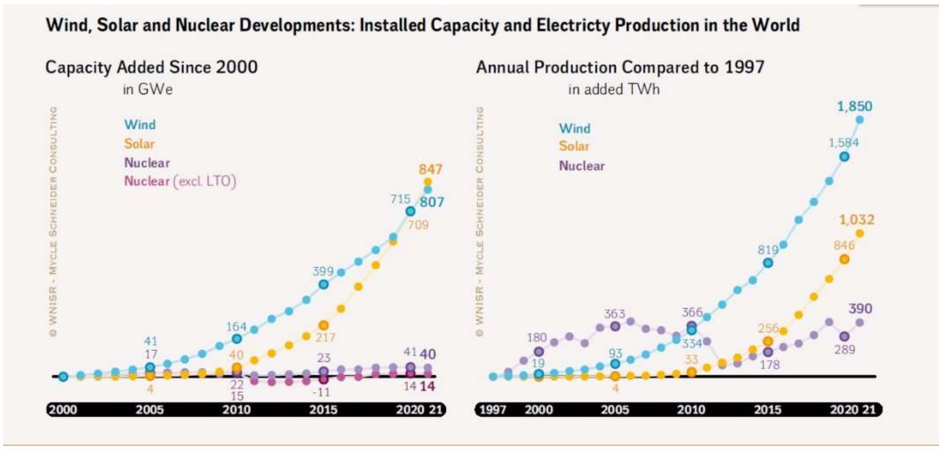
Solar PV deployment continues to boom, with an additional 138 GW according to IRENA (175 GW according to REN21) being installed in 2021, and increase in 25 percent, taking the global total to 848.5 GW (942 GW according to REN21). (WNISR 2022)

- In 2019, for the first time, non-hydro renewables—solar, wind, and mainly biomass—generated more power than nuclear plants.
- In 2020, with the significant drop of nuclear output, the gap widened, and renewables generated globally 16.5 percent more electricity than nuclear reactors.
- In 2021, wind and solar alone reached a 10.2 percent share of power generation, "the first time, wind and solar power have provided more than 10 percent of global power and surpassing the contribution of nuclear energy", as BP notes in its Statistical Review 2022.

Figure 2 illustrates the extent to which renewables have been deployed since the start of the millennium, an increase in capacity of 807 GW for wind and of 847 GW for solar, according to IRENA, compared to the relative stagnation of nuclear power capacity, which over this period increased by around 40 GW, including all reactors currently in Long-Term Outage (LTO).

The characteristics of electricity generating technologies vary due to different load factors. In general, over the year, operating nuclear power plants produce more electricity per installed MW than renewables. However, as can be seen in Figure 2, compared to 1997, when the Kyoto Protocol was signed, there has been an additional 1,850 TWh of wind power and 1,032 TWh more solar power generated in 2021, compared to an additional 390 TWh (net) of nuclear energy. In other words, over that 23-year period, wind turbines and solar panels added considerably more low-carbon electricity to the world's grids than nuclear power.

[3] REN21, "Renewables 2022—Global Status Report", June 2022



Sources: WNISR with IAEA-PRIS, IRENA, BP Statistical Review, 2022

Figure 2: Wind, Solar and Nuclear Development: Installed Capacity and Electricity in the world (WNSIR 2022)

Worldwide, the expansion of nuclear power plants has largely stagnated following the construction boom of the 1970s and 80s. Since the 1990s, electricity generated by nuclear power plants has remained at around 2,600 TWh per year. Its share of total electricity generation, however, has been declining since its historic high of 17.6 percent in 1996. In 2021, the nuclear share was below ten percent for the first time in decades. In contrast, the share of renewable energy is continuously increasing. (DIW 2023)

The nuclear share of electricity generation will continue to decline. Over the next few years, a large number of nuclear power plants will be taken offline due to their advanced age. These extensive shutdowns are offset by only 53 new construction projects (approximately 50 GW) currently underway. Twenty-six of the current new construction projects are currently experiencing delays in planning, approval, or completion—in some cases by a significant amount of over ten years. On the other hand, the expansion of renewable energy sources is increasing continuously and will continue to reduce the nuclear share in the electricity mix, partially due to the expansion of electrification in the future. (DIW 2023)

4.1 Increase of energy production from renewables in the EU

In the European Union (EU), renewables, including hydro, continue to grow and for the first time they overtook fossil fuels to become the primary source of power in 2020. Renewables rose to generate 38 percent of Europe's electricity in 2020, with fossil fuels falling to 37 percent. Coal fell by 20 percent in the year, halved its production from 2015, and gas-produced electricity decreased by 4 percent. Nuclear generation fell by 11 percent, its largest fall since 1990. Wind generation rose 9 percent in 2020 and solar production rose 15 percent, together generating a fifth of Europe's electricity in 2020 (wind 14 percent, solar 5 percent). 2020 is the first year that non-hydro renewables generate with 702 TWh more power than nuclear reactors with 652 TWh in the EU27 (see Figure 3). (WNISR 2021)

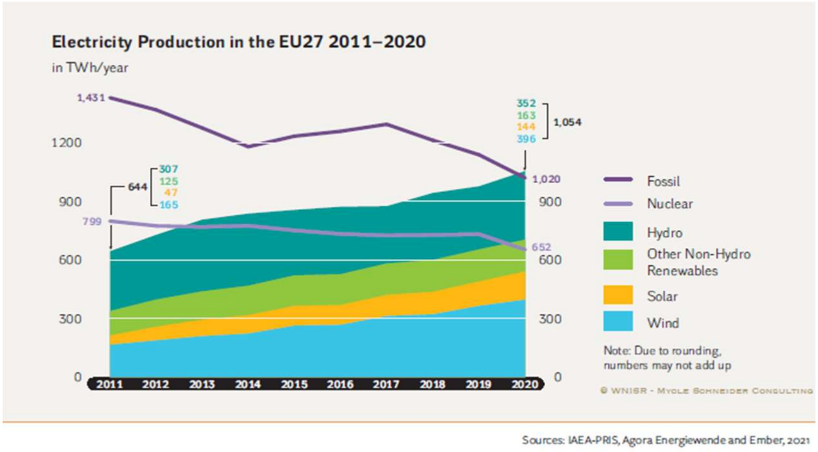


Figure 3: Electricity Generation in the EU27 by Fuel 2011-2020 (WNISR 2021)

5. Electricity generation from renewable energies is considerably cheaper than electricity generation from nuclear power plants.

The annual Levelized Cost of Energy (LCOE) analysis for the U.S. last updated by Lazard, one of the oldest banks in the world, in October 2021, suggests that unsubsidized average electricity generating costs declined on average between 2009 and 2021 in the case of solar PV (crystalline, utility-scale) from US$359 to US$36 per MWh, a fall of 90 percent, and for wind from US$135 to US$38 per MWh (a 72 percent fall), while nuclear power costs went up from US$123 to US$167 per MWh, an increase of 36 percent[4] (WNISR 2022)

Globally, the cost of renewables is now significantly below that of either nuclear power or gas. According to a 2020 Bloomberg New Energy Finance (BNEF) analysis, wind and solar power are now the cheapest form of new electricity in most of the world. Furthermore, BNEF anticipated that it will be more expensive to operate existing coal or natural gas power plants within five years than to build new solar or wind farms.[5] (WNISR 2022)

In their annual review of renewable energy costs, the International Renewable Energy Agency (IRENA) concludes that in the single year 2021, the global weighted-average LCOE from new capacity additions of onshore wind declined by 15 percent to US$33/MWh compared to 2020. Over the same period, the LCOE of utility-scale photovoltaics was also down 13 percent, nearly double the rate the year before.[6] (WNISR 2022)

IRENA agrees with BNEF and calculated that 800 GW of existing coal-fired capacity in the world have higher operating costs than new utility-scale solar PV at US$57/MWh and onshore wind at US$39/MWh, including US$5/MWh for additional system integration costs. Replacing these coal-fired plants would cut annual system costs by US$32 billion per year and reduce annual emissions by around 3 billion tons of CO_2. The same logic applies to the operation of nuclear power plants. The running of aging nuclear power plants generally leads to higher operating and maintenance costs. (WNISR 2022)

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[4] Lazard, "Lazard's Levelized Cost of Energy Analysis —Version 15.0", October 2021, see https://www.lazard.com/media/451905/lazards-levelized-cost-of-energy-version-150-vf.pdf

[5] Jeremy Hodges, "Wind, Solar Are Cheapest Power Source In Most Places, BNEF Says", *Bloomberg*, 19 October 2020, see https://www.bloomberg.com/news/articles/2020-10-19/wind-solar-are-cheapest-power-source-in-most-places-bnef-says .

[6] IRENA, "Renewable Power Generation Costs in 2021", International Renewable Energy Agency, July 2022, see https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021 .

Since 2009, when Lazard started publishing its LCOE estimates in the current format, solar PV costs dropped by 90 percent, onshore wind by 70 percent, while nuclear power increased by one third. (WNISR 2021)

In their annual review of renewable energy costs, the International Renewable Energy Agency (IRENA) concludes: "*In 2020, the global weighted average levelized cost of electricity (LCOE) from new capacity additions of onshore wind declined by 13%, compared to 2019. Over the same period, the LCOE of offshore wind fell by 9% and that of utility-scale photovoltaics (PV) by 7%.*"[7]

5. 1 Investing in Renewables Save More Carbon per Year and Dollar

An assessment finds that new nuclear plants take 5–17 years longer to build than utility-scale solar or onshore wind power[8], so existing fossil-fuelled plants emit far more CO_2 while awaiting substitution. (WNISR 2019)

The US National Renewable Energy Laboratory (NREL) expected in 2018 that onshore wind power would get 27 percent cheaper during 2016–2050 and photovoltaics 60 percent, so by 2050 they should cost respectively around US$27/MWh and US$18/MWh in good sites. **Nuclear new-build thus costs many times more per kWh, so it buys many times less climate solution per dollar, than the renewables**. **That reality could usefully guide policy and investment decisions if the objective is to save money or the climate or both. This gap is widening as nuclear costs keep rising and renewable costs falling.**

The evidence suggests that closing many, perhaps most, operating nuclear units will not directly save CO_2, but can indirectly save CO_2, if the nuclear plant's operating costs are reinvested in efficiency or cheap modern renewables that in turn displace more fossil-fuelled generation. Therefore, closing both coal plants and costly-to-run nuclear plants (with reinvestment of avoided operating costs and subsidies) makes sense—the former to save carbon directly, and the latter to save money whose climate-effective reinvestment can then save more carbon. (WNISR 2019)

Moreover, plant-to-operation times are rather long – 10–19 years for each nuclear power plant. For the nuclear plants in the EU, these times are even longer. Considering the projects in two Finland and France the PTO time is more than 20 years.

Any major expansion of nuclear energy would delay the decommissioning of fossil-fired power plants, as the latter would have to remain in operation during this period and therefore make it hard to achieve the climate change mitigation objective. It is even possible to argue that nuclear energy hinders the use of other alternatives with low CO_2 emissions because of its high capital intensity. Otherwise, this capital could be used to expand alternative energy sources like sun, wind and water (STAGL 2020).

6. The JCR Report uses unrealistic forecasts for nuclear energy without consideration of existing scenarios/forecasts for renewable energies.

The JRC Report (Part A 3.2.1 and 3.2.2) presents an assessment of using nuclear energy in terms of its contribution to climate protection according to Article 10 Para. 1 of the Taxonomy Regulation. The JRC Report compares the contribution made to climate protection by generating nuclear energy and other energy generation options in Part A 3.2.2. **It is based on a very optimistic forecast about using nuclear energy in the EU in Part A 3.2.1, p. 35ff of the JRC Report.** (BASE 2021)

[7] IRENA, "Renewable Power Generation Costs in 2020", June 2021, see www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020.

[8] Mark Z. Jacobson, "Evaluation of Nuclear Power as a Proposed Solution to Global Warming, Air Pollution, and Energy Security", *Cambridge University Press*, 15 June 2019.

The JRC Report (Part A 3.2.1) contains an estimate of the proportion of electricity generated using nuclear energy globally and in the EU in order to underline the great importance of using nuclear energy in Europe.

The JRC Report presents the contribution of nuclear power plants to greenhouse gas emissions in a very positive light. The forecast for the ongoing development of using nuclear energy for power generation in the EU, as presented in the JRC Report, is also clearly far too optimistic. The JRC Report quotes enormous volumes of new NPP capacities of 100 GW in 2050 (Figure 3.2-4), which is certainly overstated. A new capacity of 100 GW would correspond to the installation of around 60 to 80 new nuclear power plants.

With regards to the contribution to climate protection that could be made by the small modular reactors (SMR), the JRC Report does not discuss the fact that they are not yet ready for market introduction – nor does it cover the unresolved issues about safety, transportation, dismantling and disposal connected with this type of reactor.

The JRC Report is too optimistic about the "substantial contribution" of nuclear energy, because building of nuclear power plants is too slow and too expensive. Many examples can be given. Poland started its nuclear program in 1974, but until now there is no NPP operational in that country. Result of the "nuclear program" is that there is little development of renewables and coal plants are the main contributor to the energy supply. In the UK, M. Thatcher called for more nuclear already in 1989; however, no new NPP has been built and only two reactors are under construction today.

All in all, it can be concluded that the statements in Part A 3.2.1 of the JRC Report about the further development of nuclear power for the electricity generation in the EU are presented in a far too optimistic way. The forecast is largely founded on one article, which is based on a model calculation. **This model calculation is taken over without any classification and without specifying any uncertainties.** The forecast that the share of nuclear energy of 22% will continue until the year 2050, while overall electricity production increases, presupposes a massive expansion of nuclear power plants in Europe. (MRAZ et al. 2021) This massive expansion cannot be assumed given that only three reactors started up since 2002: one each in the Czech Republic, Romania, and Finland. After Cernavoda-2 was connected to the grid in Romania in 2007, the next and latest reactor the many times delayed Olkiluto-3 was connected to the grid in March 2022 but is still not in commercial operation. **The JRC Report projected 10 new reactors in 2025 and 20 new reactors in 2030. The reality is completely different: with a planning-to-operation time of about 20 years, only the two new reactors Flamanville 3 and Olkiluoto 3 will most likely be in operation in 2030. The contrast between the importance of nuclear power in the modeling of energy scenarios despite its clear lack of operational competitiveness is also known as the nuclear power modeling paradox[9].**

Moreover, the JRC Report still uses the database of EU28, i. e. including the United Kingdom (BASE 2021). The United Kingdom made a major contribution to the installed capacity in the EU with its 15 reactors in operation at that time[10], however the UK left the EU 31 January 2020.

The forecast presented in the JRC Report not only presupposes the construction of new nuclear power plants, but also the extensive retrofitting of the ageing nuclear power plants in the EU: the first cases of decommissioning of nuclear power plants in the JRC Report (Figure 2.3–4) are not envisaged until the year 2040. This would imply a lifetime for all the nuclear power plants within the EU of about 60 years, although this is unlikely because of shut-downs that have already been announced, including those in Germany. (BASE 2021)

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[9] Christian von Hirschhausen, "Nuclear Power in the Twenty-first Century – An Assessment (Part I)," *DIW Discussion Paper*, no. 1700 (2017)

[10] Six reactors have since been permanently shut down.

Most of the nuclear power plants currently operating in the EU are more than 30 years old, 90 of the 104 currently in service in the EU are between 31 and 40 years old and 30 are actually more than 40 years old. (WNISR 2022)

The nuclear power plants were originally designed for a lifetime between 30 and 40 years. The degree to which national authorities will actually approve a lifetime extension to the service life of old units in accordance with the current safety requirements is uncertain – as is required for the forecast in the JRC Report – and will depend on the status of the reactors concerned and the respective national regulatory framework. The problems with ageing related effects show that the lifetime extension is not always possible or only possible when a higher risk for the population is accepted and/or with high investments.

This very positive presentation of future prospects for the use of nuclear energy, which is shown in the JRC Report, must be critically considered. **Even if these forecasts cannot play a role when assessing nuclear energy according to the specific environmental objectives of the EU taxonomy, this presentation by the JRC appears to be biased and possibly indicates a lack of adequate independence.** Large parts of society struggle to accept nuclear energy.

Forecast IEA

The International Energy Agency (IEA) is struggling to improve its renewables forecasting: since 2002, it has raised wind power forecasts sixfold and solar forecasts 23-fold without ever catching up with reality, so installed solar capacity is now over 50 times the 2002 forecast. That's because IEA's renewable cost projections lag the market, and because its forecasting model, like other conventional economic models, is structurally unable to handle increasing returns. (WNISR 2021)

In 2021, climate change was high on the political agenda as governments and companies prepared for the 26th meeting of the parties of the United Nations Framework Convention on Climate Change (COP26, UNFCCC) in November. This was to be a vital meeting of the UNFCCC as all parties were expected to review and revise their Nationally Determined Contributions (NDCs), which contain their adaptation and mitigation plans until 2030 and therefore increase their carbon reduction plans.

In preparation for COP26, the IEA published a report outlining a strategy for the energy sector to meet the temperature targets of the Paris Agreement and concluded that in their scenario, "*by 2050, almost 90% of electricity generation comes from renewable sources, with wind and solar PV together accounting for nearly 70%.*"[11]This is a remarkable perspective from the IEA, which in its scenarios has so long systematically underestimated and downplayed the role for renewable energy. (WNISR 2022)

7. 100% Renewables Scenarios are able to deal with variability and stability.

According to BREYER et al. (2022), much of the resistance towards 100% RE systems in the literature seems to come from the a-priori assumption that an energy system based on solar and wind is impossible since these energy sources are variable. Critics of 100% RE systems like to contrast solar and wind with 'firm' energy sources like nuclear and fossil fuels (often combined with CCS) that bring their own storage. This is the key point made in the critical articles, such as those by Clack *et al.*, Trainer, Heard *et al.* [12]

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[11] IEA, "Net Zero by 2050 – A Roadmap for the Global Energy Sector", International Energy Agency, May 2021, see https://www.iea.org/reports/net-zero-by-2050

[12] **C. T. M. Clack**, ``Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar," *Proc. Nat. Acad. Sci. USA*, vol. 114, no. 26, pp. 6722-6727, Jun. 2017, doi: 10.1073/pnas.1610381114. **T. Trainer**, ``Some problems in storing renewable energy," *Energy Policy*, vol. 110, pp. 386-393, Nov. 2017, doi: 10.1016/j.enpol.2017.07.061. **B. P. Heard**, B. W. Brook, T. M. L. Wigley, and C. J. A. Bradshaw, ``Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems," *Renew. Sustain. Energy Rev.*, vol. 76, pp. 1122-1133, Sep. 2017, doi: 10.1016/j.rser.2017.03.114.

However, while it is true that keeping a system with variable sources stable is more complex, a range of strategies can be employed that are often ignored or underutilized in critical studies:

- oversizing solar and wind capacities; strengthening interconnections[13];
- demand response, e.g. smart electric vehicles charging using delayed charging or delivering energy back to the electricity grid via vehicle-to-grid[14];
- storage[15], such as stationary batteries;
- sector coupling[16], e.g. optimizing the interaction between electricity, heat, transport, and industry;

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[13] **M. Z. Jacobson**, ``The cost of grid stability with 100% clean, renewable energy for all purposes when countries are isolated versus interconnected," *Renew. Energy*, vol. 179, pp. 1065-1075, Dec. 2021, doi: 10.1016/j.renene.2021.07.115.; **R. A. Rodríguez**, S. Becker, G. B. Andresen, D. Heide, and M. Greiner, ``Transmission needs across a fully renewable European power system," *Renew. Energy*, vol. 63, pp. 467-476, Mar. 2014, doi: 10.1016/j.renene.2013.10.005. ; **T. Brown**, D. Schlachtberger, A. Kies, S. Schramm, and M. Greiner, ``Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system," *Energy*, vol. 160, pp. 720-739, Oct. 2018, doi: 10.1016/j.energy.2018. 06.222.; **A. Gulagi**, M. Ram, and C. Breyer, ``Solar-wind complementarity with optimal storage and transmission in mitigating the monsoon effect in achieving a fully sustainable electricity system for India," in *Proc. 1st Int. Conf. LS Grid Integ RE India*, 2017. [Online]. Available: https://www.researchgate.net/publication/319516069. **M. Victoria**, N. Haegel, I. M. Peters, R. Sinton, A. Jäger-Waldau, C. del Cañizo, C. Breyer, M. Stocks, A. Blakers, I. Kaizuka, K. Komoto, and A. Smets, ``Solar photovoltaics is ready to power a sustainable future," *Joule*, vol. 5, no. 5, pp. 1041-1056, May 2021., **M. Child**, C. Kemfert, D. Bogdanov, and C. Breyer, ``Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe," *Renew. Energy*, vol. 139, pp. 80-101, Aug. 2019, doi: 10.1016/j.renene.2019.02.077.

[14] **A. Pfeifer**, V. Dobravec, L. Pavlinek, G. Kraja£i¢, and N. Dui¢, ``Integration of renewable energy and demand response technologies in interconnected energy systems," *Energy*, vol. 161, pp. 447-455, Oct. 2018, doi: 10.1016/j.energy.2018.07.134.; **O. Johanna**, ``The Impact of ERS on the electricity system-An energy system model comparison for Sweden and Germany," in *Proc. 3rd Electr. Road Syst. Conf. Frankfurt Am Main, Ger.*, 2019. [Online]. Available: https://electricroads.org/wp-content/uploads/ersconference- 2019/abstracts/S6_-_Olovsson_et_al_-_The_Impact_of_ ERS_on_the_electricity_system_-_an_energy_system_model_comparison_for_S.pdf ; **H. C. Gils**, ``Economic potential for future demand response in Germany-Modeling approach and case study," *Appl. Energy*, vol. 162, pp. 401-415, Jan. 2016, doi: 10.1016/j.apenergy.2015.10.083. **L. Juuso**, N. Rami, and L. P. D., ``Effectiveness of smart charging of electric vehicles under power limitations," *Arch. Thermodyn.*, vol. 33, no. 4, pp. 23-40, 2013, doi: vol. 38.pp. 404-414. **M. Child**, A. Nordling, and C. Breyer, ``The impacts of high V2G participation in a 100% renewable Åland energy system," *Energies*, vol. 11, no. 9, p. 2206, Aug. 2018, doi: 10.3390/en11092206. **T. Boström**, B. Babar, J. B. Hansen, and C. Good, ``The pure PV-EV energy system-A conceptual study of a nationwide energy system based solely on photovoltaics and electric vehicles," *Smart Energy*, vol. 1, Feb. 2021, Art. no. 100001, doi: 10.1016/j.segy.2021.100001.

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[16] **B. V. Mathiesen**, H. Lund, D. Connolly, H. Wenzel, P. A. Østergaard, B. Möller, S. Nielsen, I. Ridjan, P. Karnøe, K. Sperling, and F. K. Hvelplund, ``Smart energy systems for coherent 100% renewable energy and transport solutions," *Appl. Energy*, vol. 145, pp. 139 -154, May 2015, doi: 10.1016/j.apenergy.2015.01.075.,; **D. Bogdanov**, A. Gulagi, M. Fasihi, and C. Breyer, ``Full energy sector transition towards 100% renewable energy

- power-to-X[17], e.g. producing hydrogen at moments when there is abundant energy; et cetera.

Using all these strategies effectively to mitigate variability is where much of the cutting-edge development of 100% RE scenarios takes place.

Maintaining **grid reliability** when solar PV and wind power (both with precisely predictable but large power fluctuations) dominate electricity generation will require changes in markets, institutions, processes, habits and thinking. Feasibility has been demonstrated in both theory and practice, as evidenced by the National Statistics reports of 75 per cent renewable energy in Scotland's annual electricity consumption (2018), 72 percent in Denmark (2017, domestic production only), 67 percent in Portugal (2018), 40 percent in peninsular Spain (2018). Solar and wind power don't need massive batteries so they can produce power steadily like big thermal plants; rather, at least eight classes of grid flexibility resources exist that are available, cost-effective, and sufficient[18] (WNISR 2019).

7.1 Example: Energy generation from biomass and biogenic waste ensures variable generation from wind and PV.

In Germany, for example about 50.4 billion kWh (11 %) of electricity was provided from biomass and biogenic waste in 2021. The installed capacity increased by about one percent to 10,431 MW in 2021. Compared to 2016, the increase in installed capacity is about 20 percent. However, the expansion of biomass plant capacity in recent years has primarily served to make electricity generation more flexible. This so-called "overbuilding" has hardly led to an increase in the amount of electricity generated annually in recent years, but it does ensure that renewable electricity can be provided more flexibly in line with demand (i.e. for example in times of low wind and PV electricity generation).[19]

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supply: Integrating power, heat, transport and industry sectors including desalination," *Appl. Energy*, vol. 283, Feb. 2021, Art. no. 116273, doi:10.1016/j.apenergy.2020.116273.; D. Connolly, H. Lund, and B. V. Mathiesen, ``Smart energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European union," *Renew. Sustain. Energy Rev.*, vol. 60, pp. 1634 -1653, Jul. 2016, doi: 10.1016/j.rser.2016. 02.025. ; **H. Lund**, A. N. Andersen, P. A. Østergaard, B. V. Mathiesen, and D. Connolly, ``From electricity smart grids to smart energy systems -A market operation based approach and understanding," *Energy*, vol. 42, no. 1, pp. 96 -102, Jun. 2012, doi: 10.1016/j.energy.2012. 04.003.; **H. Lund**, P. A. Østergaard, D. Connolly, and B. V. Mathiesen, ``Smart energy and smart energy systems," *Energy*, vol. 137, pp. 556 -565, Oct. 2017, doi: 10.1016/j.energy.2017.05.123.; **M. Robinius**, A. Otto, K. Syranidis, D. S. Ryberg, P. Heuser, L. Welder, T. Grube, P. Markewitz, V. Tietze, and D. Stolten, ``Linking the power and transport sectors -Part 2: Modelling a sector coupling scenario for Germany," *Energies*, vol. 10, no. 7, p. 957, Jul. 2017, doi: 10.3390/en10070957., **T. Brown,** D. Schlachtberger, A. Kies, S. Schramm, and M. Greiner, ``Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system," *Energy*, vol. 160, pp. 720 -739, Oct. 2018, doi: 10.1016/j.energy.2018. 06.222.; **J. C. Osorio-Aravena**, A. Aghahosseini, D. Bogdanov, U. Caldera, N. Ghorbani, T. N. O. Mensah, S. Khalili, E. Muñoz-Cerón, and C. Breyer, ``The impact of renewable energy and sector coupling on the pathway towards a sustainable energy system in Chile," *Renew. Sustain. Energy Rev.*, vol. 151, Nov. 2021, Art. no. 111557, doi: 10.1016/j.rser.2021.111557.

[17]**M. Sterner** and M. Specht, ``Power-to-gas and power-to-X-The history and results of developing a new storage concept," *Energies*, vol. 14, no. 20, p. 6594, Oct. 2021, doi: 10.3390/en14206594. ; **M.Victoria**, E. Zeyen, and T. Brown, ``Speed of technological transformations required in Europe to achieve different climate goals," *Joule*, vol. 6, no. 5, pp. 1066-1086, May 2022, doi: 10.1016/j.joule.2022.04.016.; **E. Kötter**, L. Schneider, F. Sehnke, K. Ohnmeiss, and R. Schröer, ``The future electric power system: Impact of power-to-gas by interacting with other renewable energy components," *J. Energy Storage*, vol. 5, pp. 113-119, Feb. 2016, doi:10.1016/j.est.2015.11.012.

[18] Amory B. Lovins, "Reliably integrating variable renewables: Moving grid flexibility resources from models to results", *The Electricity Journal*, Volume 30, Issue 10, December 2017, see https://doi.org/10.1016/j.tej.2017./11.006.

[19] Umweltbundesamt: Erneuerbare Energien in Zahlen; https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen?sprungmarke=strom#strom

8. The baseload concept is not needed for the transition to 100 % Renewables Energy Supply but counterproductive.

The "baseload" concept that grid stability needs gigawatt-scale, steadily operating thermal (steam-raising) power plants reflects the valid economic practice of dispatching power at least operating cost, so resources with lowest operating costs are run most. This traditional role of giant thermal plants led many people to suppose that such plants are always needed. But now that renewables with no fuel cost are taking over the "baseload" role of being dispatched whenever available, those big thermal plants are relegated to fewer operating hours, making the term "baseload" an obsolete honorific. Thermal plants must now adapt to follow the net load left after cost-effective efficiency, demand response, and real-time "base-cost" renewable supply have been dispatched. **Nuclear power's limited flexibility, and its technical and economic challenges when cycled, have thus become a handicap, complicating least-cost and stable grid operation with a rising share of zero-carbon, least-cost variable renewables.**[20] That is why Pacific Gas and Electric Company (PG&E) in the United States found that early closure of its well running Diablo Canyon reactors would save customers money and, by making the grid more flexible, raise renewables' share. (WNISR 2019)

9. Security of energy supply and grid integrations costs

An argument often claims that more renewables mean steeply rising grid integration costs. But such effects would be worse for nuclear-dominated grids because nuclear plants are bigger, more transmission-dependent, and more prone to sudden, lengthy, unpredictable failures (see for example France). No kind of plant is running 24/7/365, but failure is more consequential in big units. Either way, renewables generally have lower backup needs and costs than nuclear plants, despite solar and wind power's much lower capacity factors. (WNISR 2019)

Comparing costs of different sources, the "Value-adjusted Levelized Costs of Energy" (VALCOE) is better. The VALCOE take into account the factors of flexibility, operating characteristics and base-load capability versus volatility (summarised under "system serviceability") in addition to the conventional LCOE. For the EU in 2019, VALCOE are given as US$145/MWh for nuclear, US$60/MWh for solar PV, US$55/MWh for onshore wind and US$80/MWh for offshore wind. By 2040, the VALCOE for nuclear power is expected to be 115 US$/MWh, for PV US$65/MWh, for wind onshore US$60/MWh and for offshore wind only US$50/MWh. (IAE 2020) **This calculation shows that even taking into account the costs of grid integration, electricity generation from renewables is significantly cheaper than electricity generation from nuclear power plants.**

9.1 Lack of security of energy supply through NPPs

Nuclear power is not a secure source of energy, as there are various outages during operation. Moreover, there are already enough flexibility options for a secure power supply. Those who think of digitalisation and climate protection together combine energy and load management, flexible demand and, in the medium term, electricity storage systems that compensate for fluctuations in the shortest possible time.

- The contribution of new nuclear power plants (NPP) to energy security is very limited due to significant time between planning and operation of NPPs.

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[20] Amory B. Lovins, "Do coal and nuclear generation deserve above-market prices?", *The Electricity Journal*, Vol.30, Issue 6, July 2017, see https://doi.org/10.1016/j.tej.2017.06.002 , notes 58–68; and C. Morris, "Backing up Wind and Nuclear Power", 2015, see www.renewablesinternational.net/backing-up-wind-and-nuclear-power/150/537/86412/..

- The contribution of SMRs to energy security is even more limited, as it will take decades before they can be used commercially.

- The contribution of the ageing nuclear power plants to energy supply security is limited. This is mostly because of the ageing related outages. In addition, there are increasing climate change related outages.

Examples for ageing related outages of NPPs in France

Proponents of nuclear power say that the reactors' relative reliability and capacity make this a much clearer choice than other non-fossil-fuel sources of energy, such as wind and solar, which are sometimes brought offline by fluctuations in natural resource availability. However, older nuclear plants are extremely inefficient and run a higher risk of disaster. (BECKER et al. 2020) Examples for ageing related outages in France are described below.

The average age of the 56 reactors is 37 years (end of 2021). In 2022, the French the annual load factor at 69 percent was still poor but improved since a record low of 55.6 percent in 2016. (WNISR 2022)

In 2018, generation performance was affected by exceptional damages and large generation incidents (costing around 12.5 TWh), longer-than-expected outages (costing around 5 TWh) and environmental constraints (costing around 2 TWh). The outage extensions experienced in 2018 were caused in equal measure by maintenance and operational quality issues, technical failures and project management deficiencies. Performance losses related to unplanned outages rose from a rate of 3.26% in 2017 to 3.7% in 2018 because of several exceptional incidents. (WNISR 2019)

Additionally, the finding of carbon segregations in the pressure vessel of new build reactor project Flamanville 3 had raised concerns about the possibility that other components could have been fabricated below technical specifications due to poor quality processes at Creosote Forge. On 25 April 2016, AREVA informed ASN that irregularities in the manufacturing checks, the quality-control procedures, were detected at about 400 pieces fabricated since 1969, about 50 of which would be installed in the French currently operating reactor fleet. The irregularities included inconsistencies, modifications or omissions in the production files, concerning manufacturing parameters or test results. According to EDF, in total, it has detected 1,775 anomalies in parts that were integrated into 46 reactors. (WNISR 2019)

In summer 2022, only half of the 56 reactors in France were operating. Only some reactors were shut-down, because of planned outages, but several because of unexpected ageing failures: Between mid-2021 and early 2022, inspections by EDF revealed corrosion and cracks in key pipes at five reactors, prompting lengthy checks and repairs. In mid-April, the company reported ultrasound inspection results suggesting that at least four additional reactors could be affected by similar problems.[21]

Subsequently, it turned out that certain 1300-MW reactors—there are 20 such units—are also showing similar symptoms and, as of mid-2022, 12 reactors are shut down for an unknown period of time due to the problem. To what extent the issue also concerns the 900 MW reactors—32 units—is yet to be seen.

After several downward revisions, as of mid-2022, EDF estimates of the annual production range at 280–300 TWh, a figure not seen since 1990.

Weather-related events in NPPs affecting the energy supply.

When thinking of possible climatic effects on the resilience of the nuclear power plants, heat waves are particularly concerning due to their impact on the temperature of the reactor's cooling water. A heat wave could increase the number of shutdowns. In 2003, for example, a heat wave forced the shutdown

[21]NuclearNewswire: France's energy woes worsened by inspection-related nuclear power plants shutdowns; 6 May 2022; https://www.ans.org/news/article-3939/frances-energy-woes-worsened-by-inspectionrelated-nuclear-power-plant-shutdowns/ ; seen 05.04.2023

of more than thirty nuclear power plants in Europe. A similar event took place in 2018 when numerous nuclear power plants all over the world, from France to South Korea, had to cease their operations due to abnormally high temperatures. These events resulted in substantial economic losses. (CAIRO 2019)

10. There are several well-known reasons, why nuclear power plants do not support the absorption of renewables, but the opposite is the case.

10.1 Nuclear power plants are not flexible.

Flexible generation is sometimes cited as a benefit of nuclear power. But, in practice, the only places where nuclear plants have been extensively used for flexible generation are countries with energy mixes that necessitate reliance on nuclear for these purposes. For example, countries with a high percentage of nuclear power (e.g., France where 70 percent of electricity is provided by nuclear plants).

Electric demand varies in a fairly predictable daily cycle: lowest at night, much higher during the day, peaking in late afternoon, and decreasing in the evening. The economics of generators following demand are not captured by levelezed cost comparisons. In the United States, nuclear plants function as baseload generators, meaning they operate nearly continuously at maximum capacity to serve the minimum amount of electricity demanded at all times. Nuclear reactors are feasibly able to vary output, but they face technical limitations. Most importantly, nuclear's large capital and low operating costs are ideally suited to continuous operation at capacity.

In January 2018, the Institute for Advanced Sustainability Studies (IASS) in Potsdam published a study evaluate the question "*Is a decarbonized electricity system with a mix of fluctuating renewables and nuclear reasonable*?". It is explained that the Germans have known about the "Systemkonflikt" (system conflict) between nuclear and wind & solar for a decade. The English-speaking world continues to debate what "dispatchable" means, whether wind and solar are "intermittent" or "variable". The German debate knows no such confusion. Facts are gas turbines are quickly dispatchable; inflexible baseload is not. Inflexible baseload (like nuclear power plants) is incompatible with fluctuating wind and solar (IASS 2018).

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.

All talk of nuclear as a possible "friend" of wind and solar or as a "bridge technology" overlooks technical conflicts. Germany has moved beyond such political compromises and accepts physical realities in energy policy. The so called "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. (IASS 2018)

The term "bridge technology" for nuclear power was probably first used in 1996 by the Commission of German Bishops[22]. 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. (IASS 2018)

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[22] Vogt, Prof. Markus**.** "Wissenschaftliche und technische Aspekte einer sicheren Energieversorgung aus der Sicht Christlicher Sozialethik Statement zur Öffentlichen Tagung der Ethikkommission." 1996. www.kaththeol.uni-muenchen.de/lehrstuehle/christl_sozialethik/personen/1vogt/texte_vogt/vogt_sichere_energie.pdf

The German Advisory Council on the Environment (SRU) published study in May 2009.[23] It found that:

- 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.

The study included a chart showing what became known as the "residual load" (power demand minus renewable power generation), which conventional plants would have to cover.

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. (IASS 2018)

To conclude: Germany's nuclear phaseout is partly based on an understanding that baseload cannot flexibly accommodate fluctuating wind and solar, 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. (IASS 2018)

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. 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.[24] (IASS 2018)

10.2 The flexible operation, the so-called load following operation, is technical problematic for NPPs.

Mostly NPPs are operated as baseload plants at a steady power level of 100%. Startup, shutdown and load changes are very infrequent. Pressurized water reactors (PWR) can rebalance small disturbances by inherent self-regulation. Thus, nuclear plants can contribute to the stabilization of the grid frequency. Operating NPPs in Europe are mainly working in baseload. Their flexibility is limited to a few two percent of nominal power.

Nuclear power plants can work in certain power range of about 50 to 100% of full power. They normally keep running on 100% power, because in the grid system it is easier to reduce wind power. The "must run" of nuclear power plants, limits the option for renewables.

Operating NPP in load-following mode causes technical disadvantages, because plant components are exposed to numerous thermal stress cycles; this leads to faster aging and requires more sophisticated systems for reactor monitoring and control. An economic disadvantage of load-following operation of NPPs in a larger power range occurs if the plants are operated on reduced power. On top is the problem, that nuclear is the most expensive electricity production and reducing the full power hours will further increase the cost per kWh and the total system cost.

There are limits for NPPs in regulating energy output in lower electricity production (lower than 30%); and to shut down a NPP and just restart it again is technical not possible. In the low power range, more fission products accumulate, which absorb neutrons. This can lead to dangerous reactor conditions

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[23] SRU "Weichenstellungen für eine nachhaltige Stromversorgung." Press release from 28 May 2009. www.umweltrat.de/SharedDocs/Pressemitteilungen/DE/2009/2009_04_pressemitteilung.html?nn=9732658.

[24] Most notably, the 2017 edition of REN21's Global Status Report contains a chapter on "Deconstructing baseload." Global Status Report 2017.

(neutron poisoning), the missing neutrons lead to a reduction in power, which is compensated by removing control rods. In the case of neutron poisoning, a reactor must be shut down until these fission products have sufficiently disappeared through radioactive decay. This is to be avoided and it is best not to let the reactor go below a certain power limit or to shut it down completely, but then it cannot be started up again immediately.

With respect to nuclear power plants, responsiveness of currently available light water reactors (LWR) is challenged by neutron poisons – in particular the isotope xenon-135 (xenon). Xenon is a powerful thermal neutron absorber (poison) and will capture neutrons otherwise available for fission of the reactor fuel. It is produced directly and indirectly from fission in all reactors. The time periods, frequency of adjustment and response time required in load-following are in direct conflict with the nature of xenon transients at NPP. For this reason, most NPP operators choose not to subject their facilities to load following operating modes. (NUTTAL 2009)

For new NPPs of Generation III (under construction and planned) load-following suggested to be fully implemented. But there is not much experience from operation practice. Investigations into the possible impacts of load-following operation are limited and do not allow conclusions on the impacts in future.

Due to economic aspects the new nuclear plants currently under construction or planned in Europe have a high capacity of 1200 to 1700 MW. Even if a high flexibility is promised for the new reactors, some more research will be necessary until load-following with the necessary capability can be implemented. Controlling the reactor core during load-following is challenging and difficult also for advanced reactors, in particular for reactors with large cores. The so called technological 'lock-in' hinders the fast deployment of the renewables.

Example for a technical problem due to load-following operation
In recent years, increased oxide-thickness on the fuel rods has been detected at several nuclear power plants in Germany that endanger. To limit the corrosion mechanism, among other measures a restriction on load-following operation has also been established.[25]

Load-following constraints in Germany and France
In the IASS (2018) study a deeper view in the load- following activities in France is presented. It is explained that a look at the data by generation unit during a day reveals 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. It is also clear, that countries with do not have a large fleet cannot cover this approach. (IASS 2018)

In a paper investigating power generation and wholesale prices, Fraunhofer ISE found that German nuclear reactors 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. (IASS 2018)

These two short examples demonstrate the difficulties of load-following operation. In France, the operator avoids actual load-following operation of the entire fleet but shuts down some reactors for a longer period of time. In Germany, the operator also avoids load-following operation, accepting negative prices for the energy generated.

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[25] Reaktor-Sicherheitskommission (RSK): Erhöhte Oxidschichtdicken im oberen Bereich von Brennstäben mit M5-Hüllrohren; Empfehlung der Reaktor-Sicherheitskommission (RSK) am 12.02.2020

10.3 Nuclear blocks the social-ecological transformation to a climate friendly energy supply

The present analysis reviews a whole range of arguments based on the most recent and authoritative scientific literature. It confirms the assessment of the paper *Climate-friendly energy supply for Germany – 16 points of orientation*, published on 22 April 2021 by **Scientists for Future** (doi.org/10.5281/zenodo.4409334) that nuclear energy cannot, in the short time remaining before the climate tips, meaningfully contribute to a climate-neutral energy system. Nuclear energy is too dangerous, too expensive, and too sluggishly deployable to play a significant role in mitigating the climate crisis. In addition, nuclear energy is an obstacle to achieving the social-ecological transformation, without which ambitious climate goals are elusive.

The ultimate challenge of the great transformation, i. e. kicking off the socio-ecological reforms that will lead to a broadly supported, viable, climate-neutral energy system, lies in overcoming the drag ("lock-in") of the old system that is dominated by fossil fuel interests. **Yet, make no mistake, nuclear energy is of no use to support this process. In fact, it blocks it. The massive R&D investment required for a dead-end technology crowds out the development of sustainable technologies, such as those in the areas of renewables, energy storage and efficiency. Nuclear energy producers, given the competitive environment they operate in, are incentivized to prevent – or minimize – investments in renewables.**[26]

10.4 "Lock-in" effect of nuclear energy hinders the growth of renewables.

Due to the very high initial costs of building nuclear power plants, amortisation of these costs is only possible if the plants have a long operation time. For this reason, the most licence holders of NPPs applied for a lifetime of old nuclear power plants beyond the planned lifetime of 30 to 40 years to 50, 60 or even 80 years. However, this will increase the risks. Furthermore, the backfitting measures required for license extensions to meet higher regulatory standards make considerable investments necessary.

Nuclear power is also highly capital-intensive. Nuclear power plants take almost ten years to build, and in the average about 20 years for the decommission. In addition, there are costs for decades of interim storage of radioactive waste and spent fuel elements, as well as for final storage for several 100,000 years. The costs for future taxpayers cannot yet be calculated because of the uncertainties that still exist and the problems that have arisen in the past.

Technology and market lock-ins can result from subsidised technologies with long lifetimes. If other technologies become more cost-efficient during the lifetime of a power plant, the market remains distorted for a considerable period of time. (STAGL 2020) This is already the case for nuclear power plants. The costs of renewable energy are already significantly lower than the cost of nuclear energy. Projections show a further increase in the cost of NPPs and a further decrease in the cost of renewables.

Environmental lock-in refers to the self-perpetuating inertia created by nature-consuming energy systems that inhibits public and private efforts to adopt alternative energy technologies. There can be numerous environmental constraints associated with nuclear energy. The first is finding suitable sites for nuclear power plants: A difficult task, as a suitable site requires low population density, exclusion of natural disaster areas and access to massive water resources (ABBOTT 2011; STAGL 2020).

After 70 years of using nuclear energy, the issue of storing highly radioactive waste with its very long-term consequences is still being not solved, mainly because of uncertainties due to unforeseen geological conditions and radioactive leakage into groundwater. (STAGL 2020)

[26] Kernenergie und Klima. In Diskussionsbeiträge der Scientists for Future (1.0, Vol. 9, pp. 1–98). Wealer, B.; Breyer, C.; Hennicke, P.; Hirsch, H.; von Hirschhausen, C.; Klafka, P.; Kromp-Kolb, H.; Präger, F.; Steigerwald, B.; Traber, T.; Baumann, F.; Herold, A.; Kemfert, C.; Kromp, W.; Liebert, W.; Müschen, K. (2021).Zenodo. https://doi.org/10.5281/zenodo.5573719

Furthermore, the clean-up of uranium mines remains an unresolved issue, as thousands of abandoned uranium mines exist in different parts of the world, the land that cannot be used for other purposes for a long time.

All in all, it is to conclude that use of nuclear energy leads to a considerable lock-in of assets. Article 16 lit. (a) TR excludes activities that "*lead to a lock-in of assets that undermine long-term environmental goals, considering the economic lifetime of those assets*".

10.5 EDF and EON (NPP owners) demand limitation of energy share of renewables

EDF and EON called in 2009 for a limit on the share of renewables so that NPPs are not hindered, this clearly proves that investment in nuclear energy hampers investments in renewables energies.

The Eon Group wanted to put the brakes on the development of renewable energies. Together with its French competitor Électricité de France (EdF), Germany's leading electricity supplier is sounding the alarm: the more wind, hydro or solar power is developed, the more the nuclear industry will fall behind.

Eon stresses that renewable energies should not be promoted "indefinitely". The government must set a maximum limit for their share of total electricity generation. Eon recommends a maximum of 33 percent; EdF demands an even lower threshold of 20 to 25 percent of electricity production.

The electricity giants' braking manoeuvre is justified in this way: Wind and solar power are subject to strong "fluctuations", which means they require very flexible market mechanisms. However, this is precisely what so-called base-load power plants do not offer. Lignite-fired and especially nuclear power plants operate quite cheaply, but their ramp-up and ramp-down is costly. The more wind and solar power are taken into account in the energy mix, the more flexibly power plants have to react and the more their profitability is affected, argues Eon.[27]

10.6 Plans for expanding nuclear power plants lack technological and economic foundations.

Under the headline "Plans for expanding nuclear power plants lack technological and economic foundations" recently scientists published an article in the DIW weekly Report.

This article is related to the EU taxonomy. The scientists emphasized in the introduction "*In Europe, the inclusion of nuclear energy in the EU taxonomy has opened up opportunities to subsidies new construction projects even more than before. This is justified with sustainability aspects, which, however, is highly controversial among experts.*"

It explained that over the past decades, the nuclear industry has failed to produce competitive reactors. The current dynamics on the energy markets are resulting in hundreds of old nuclear power plants being taken offline. In Germany, as well as in the rest of Europe and worldwide, there are enough cost-efficient renewable energy sources available for a climate-neutral and plutonium-neutral energy system. (DIW 2023)

Current generation of light-water reactors have major construction delays and are overpriced. Currently, the only realistic option for building nuclear power plants is to use existing technology, namely Generation III light-water reactors (LWR), which range from 600 to 1,600 megawatts (MW) of capacity. LWR reactors include the French European Pressurized Reactor (EPR); the American AP 1000 (manufactured by Westinghouse), and the Russian VVER 1200 (manufactured by the Russian state-owned enterprise Rosatom).

[27] Frankfurter Rundschau: Stromriesen contra Windkraft; 25.03.2009 https://www.fr.de/wirtschaft/stromriesen-contra-windkraft-11479534.html

The expansion of LWR reactors, especially water-cooled thermal reactors, reached its peak in the 1970s and 80s. In the following decades, however, expansion worldwide, especially in the USA and Europe, experienced a sharp decline due to high costs and constant construction delays, among other issues.[28] Current cost analyses and comparisons with renewable energy technologies, whose electricity production costs are less than 100 US$ per MWh, show that the currently massively high construction costs for nuclear power plants would need to be reduced by two-thirds to maintain a ten percent share of electricity production in a decarbonized European energy system.[29] Contrary to original expectations, the construction of nuclear power plants has not become more affordable over the decades, but rather has become continuously more expensive (per kilowatt of capacity). Moreover, it never became possible to leverage the standardization and mass production advantages achieved in other industries (such as for chip production and solar panels).[30]

Hopes for radical innovations and the expansion of reactor concepts that have not been tested at an industrial level seem unfounded in light of the experiences of the past decades. The idea of constructing low-capacity power plants was realized in the 1950s. However, it was quickly abandoned as a result of structural cost disadvantages. This, too, is why no improvements can be expected in SMRs as of 2023. Although some countries are attempting to revive non-light-water reactors, which have not been utilized to date, an industrial breakthrough in the coming decades is unlikely. Therefore, efforts should not be focused on researching allegedly new reactor concepts.

Taking into account current trends and data, nuclear energy remains far inferior to renewable energy sources in terms of costs.

The following implications they derived from their analysis: In the context of research funding, policymakers should, in the future, focus on areas that can be expected to make substantial contributions to the energy transition, such as renewable energy sources, storage, and other flexibility options. Nuclear energy is not one of these areas. Policymakers should resolutely oppose efforts to label energy produced by nuclear power plants, such as hydrogen, as "green" or "sustainable." When designing the electricity sector in Germany and Europe, solutions aimed at subsidizing nuclear plants (as in France and Poland, for example) should be rejected.

10.7 NPPs are not necessary but counterproductive.

Stabilizing the climate is urgent, but nuclear power is slow. It meets no technical or operational need that these low-carbon competitors cannot meet better, cheaper, and faster. Even continuing to operate the old reactors saves less carbon per dollar per year than reinvesting their avoidable operating costs in renewables. Whatever the rationales for continuing and expanding nuclear power, for climate protection it has become counterproductive, and the new subsidies and would dramatically slow this decade's progress toward cheaper, faster options, more climate-effective solutions of renewables. (WNSIR 2019)

Worldwide, nuclear is already significantly more expensive than alternatives like solar photovoltaics (PV) and wind power and the disadvantage is growing fast. Available cost-effective energy resources from these renewables are huge, and their modularity, small unit size and short lead times typically make them a more rapid means to carbon emissions abatement. Where once nuclear advocates claimed that 'firm' (inflexibly-steady) nuclear output is an advantage, grid operators now recognize that new network technologies render the underlying idea of 'baseload' power to be "*outdated*".

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[28] Ben Wealer et al., "Kernenergie und Klima," *Diskussionsbeiträge der Scientists for Future*, no. 9 (2021): 1–98 (in German; available online).

[29] Leonard Göke and Alexander Wimmers, "Economic Efficiency of Nuclear Power in Decarbonized Energy Systems," (speech, Vienna, Austria, February 16, 2022) (in German; available online).

[30] Chapter 4 in Christian von Hirschhausen, *Atomenergie: Geschichte und Zukunft einer riskanten Technologie*, 1st ed. (Munich: C.H. Beck, 2023).

Objections to renewables are often raised, whether expressed as technical issues or as hidden costs. These become ever less convincing as experience gives grid operators comfort with new ways of operating power systems, and as major heavy-electricals firms like General Electric, Siemens, Schneider and Asea Brown Boveri (ABB) refocus their skills from nuclear power to distributed and renewable energy systems. (WNSIR 2019)

Conclusion of a recent published study in Germany: An additional inelastic feed-in of several GW, as would be the case with nuclear power plants, could lead to massive negative effects on the German electricity market for the expansion of renewable energies and the national economy. (BEE 2023)

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