Economic efficiency of nuclear power in decarbonized energy systems

(2) Energieerzeugung/-infrastruktur und Netze
Alexander WIMMERS[1(1)], Leonard GÖKE[(1)]
[(1)]Fachgebiet für Wirtschafts- und Infrastrukturpolitik, TU Berlin, Germany

Motivation

In addition to renewable energy strategies, several governments are increasing previously stated efforts for the construction of new nuclear power plants or re-considering this option to combat climate change and reduce fossil fuel dependencies (Stirling and Johnstone 2018; Goldstein and Qvist 2019; Schneider et al. 2022; Zakeri et al. 2022). Nuclear power can be advantageous, by possibly providing flexible operation (Jenkins et al. 2018; Lynch et al. 2022) or helping in decarbonization efforts through low-carbon electricity provision to various sectors (Luderer et al. 2021; Bogdanov et al. 2021). However, from an economic perspective, nuclear power is becoming increasingly expensive as capital costs sore for current new build projects in OECD countries (Lovins 2022; Rothwell 2022), while renewable energy technologies, such as wind and solar, are becoming cheaper (Lazard 2021) and options to manage flexible electricity production are becoming more sophisticated (Wang et al. 2018; Schill and Zerrahn 2020). We therefore ask whether nuclear power is a cost-efficient technology in a future decarbonized energy system.

Method

To answer this question, we follow a two-step approach. First, we conduct a detailed analysis of projected and actual costs of nuclear power plant projects to determine the conceivable range of levelized cost of energy (LCOE), discuss nuclear industry projections and actual reported figures as well as provide a comparison to alternative technologies, namely renewable. This analysis includes various papers, studies and reports and provides a detailed insight on nuclear cost components, beginning with the major component, capital cost, over operational cost to indirect influences such as construction time and capacity factors (Haas, Thomas, and Ajanovic 2019; Wealer et al. 2021). The analysis of results is limited to gigawatt-sized light-water-reactors in OECD countries. Second, using results obtained in the cost analysis, the efficient share of nuclear power in a decarbonized energy system is computed using a comprehensive techno-economic model (Göke 2021a; 2021b). With previous research limiting flexibility options such as cross-border exchange, demand-side flexibility and focusing on short-term storage systems (Duan et al. 2022; Baik et al. 2021), this model, focusing on Europe, considers all alternatives to nuclear power for electricity and flexibility.

Results and Conclusion

Results of the cost analysis show that a discrepancy lies, especially for nuclear capital costs, between projected costs or model assumptions and actually observed figures, see Figure 1. Additionally, OECD countries report, on average, higher costs than non-OECD countries, esp. China. Other cost components also vary, but not as prominent. From this analysis, we determine a broad range for nuclear LCOE, and therefore compute multiple scenarios with a capital cost range of 2,000 to 8,000 USD_{2018}/kW and favorable assumptions for other components and parameters. As shown in Figure 2, share of nuclear in electricity generation depends highly on the assumed capital cost. Most notably, this share does not exceed 50% even at the lowest cost level and quickly drops once higher costs are assumed. Cost ranges in which a measurable share of nuclear power is installed are in the low-range of projections and well below actually reported project costs.
To conclude, we find that capital costs for nuclear must fall significantly to become economically viable compared to alternative technologies in a decarbonized energy system. Whether this can be achieved, is disputed in literature (Grubler 2010; Koomey, Hultman, and Grubler 2017). However, non-electrical uses of nuclear power for, e.g., process heat and the application of non-light-water technologies might

[1](Jungautor) TU Berlin, Fachgebiet Wirtschafts- und Infrastrukturpolitik (WIP), Sekretariat H33, Straße 17. Juni 135, 10623 Berlin, +49 (0)30-314-75837, awi@wip.tu-berlin.de; wip.tu-berlin.de

change this assessment (Ingersoll et al. 2014; Al-Othman et al. 2019). This techno-economic cost analysis neglects costs for nuclear waste management and decommissioning (Lordan-Perret, Sloan, and Rosner 2021; Wealer et al. 2021; Lovins 2022) and does not assess non-economic disadvantages of nuclear power such as the risk of severe nuclear accidents, proliferation and radioactive contamination (Lévêque 2014; Nuttall 2022; Schneider et al. 2022).

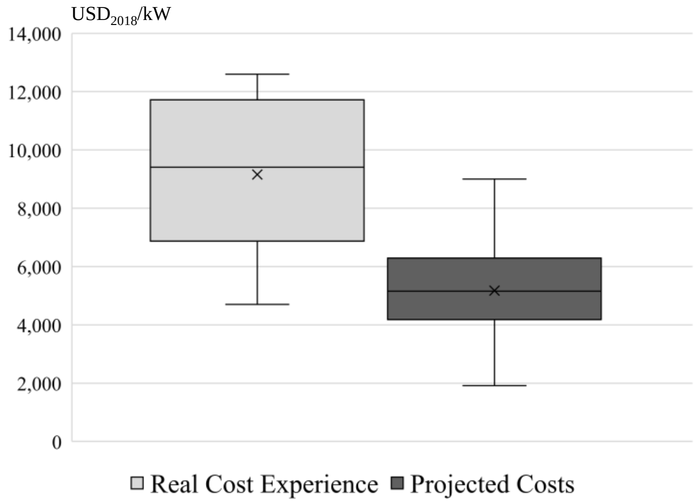

Figure 1: Results of cost analysis comparing projected and actually observed capital costs for light-water reactor projects in OECD countries.

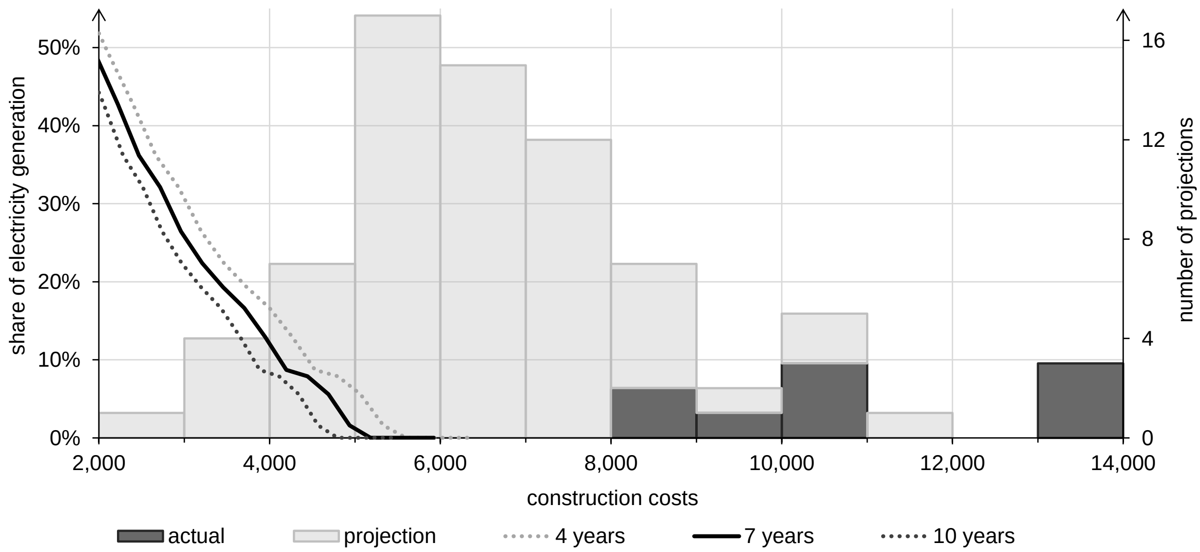

Figure 2: Computed share of nuclear energy depending on construction cost and a range influenced by construction time.

References

Al-Othman, Amani, Noora N. Darwish, Muhammad Qasim, Mohammad Tawalbeh, Naif A. Darwish, and Nidal Hilal. 2019. “Nuclear Desalination: A State-of-the-Art Review.” *Desalination* 457 (May): 39–61. https://doi.org/10.1016/j.desal.2019.01.002.

Baik, Ejeong, Kiran P. Chawla, Jesse D. Jenkins, Clea Kolster, Neha S. Patankar, Arne Olson, Sally M. Benson, and Jane C.S. Long. 2021. “What Is Different about Different Net-Zero Carbon Electricity Systems?” *Energy and Climate Change* 2 (December): 100046. https://doi.org/10.1016/j.egycc.2021.100046.

Bogdanov, Dmitrii, Manish Ram, Arman Aghahosseini, Ashish Gulagi, Ayobami Solomon Oyewo, Michael Child, Upeksha Caldera, et al. 2021. “Low-Cost Renewable Electricity as the Key

Driver of the Global Energy Transition towards Sustainability.” *Energy* 227 (July): 120467. https://doi.org/10.1016/j.energy.2021.120467.

Duan, Lei, Robert Petroski, Lowell Wood, and Ken Caldeira. 2022. “Stylized Least-Cost Analysis of Flexible Nuclear Power in Deeply Decarbonized Electricity Systems Considering Wind and Solar Resources Worldwide.” *Nature Energy*, February. https://doi.org/10.1038/s41560-022-00979-x.

Göke, Leonard. 2021a. “A Graph-Based Formulation for Modeling Macro-Energy Systems.” *Applied Energy* 301 (November): 117377. https://doi.org/10.1016/j.apenergy.2021.117377.

———. 2021b. “AnyMOD.Jl: A Julia Package for Creating Energy System Models.” *SoftwareX* 16 (December): 100871. https://doi.org/10.1016/j.softx.2021.100871.

Goldstein, Joshua S., and Staffan A. Qvist. 2019. *A Bright Future: How Some Countries Have Solved Climate Change and the Rest Can Follow*. First edition. New York: PublicAffairs.

Grubler, Arnulf. 2010. “The Costs of the French Nuclear Scale-up: A Case of Negative Learning by Doing.” *Energy Policy* 38 (9): 5174–88. https://doi.org/10.1016/j.enpol.2010.05.003.

Haas, Reinhard, Stephen Thomas, and Amela Ajanovic. 2019. “The Historical Development of the Costs of Nuclear Power.” In *The Technological and Economic Future of Nuclear Power*, edited by Reinhard Haas, Lutz Mez, and Amela Ajanovic, 97–116. Wiesbaden: Springer VS. https://doi.org/10.1007/978-3-658-25987-7_12.

Ingersoll, D, Z Houghton, R Bromm, M McKellar, and R Boardman. 2014. “Extending Nuclear Energy to Non - Electrical Applications.” The 19th Pacific Basin Nuclear Conference (PBNC 2014). https://inldigitallibrary.inl.gov/sites/sti/sti/6303857.pdf.

Jenkins, Z. Zhou, R. Ponciroli, R.B. Vilim, F. Ganda, F. de Sisternes, and A. Botterud. 2018. “The Benefits of Nuclear Flexibility in Power System Operations with Renewable Energy.” *Applied Energy* 222 (July): 872–84. https://doi.org/10.1016/j.apenergy.2018.03.002.

Koomey, Jonathan, Nathan E. Hultman, and Arnulf Grubler. 2017. “A Reply to ‘Historical Construction Costs of Global Nuclear Power Reactors.’” *Energy Policy* 102 (March): 640–43. https://doi.org/10.1016/j.enpol.2016.03.052.

Lazard. 2021. “Lazard’s Levelized Cost of Energy Analysis.” Analysis 15.0. Lazard’s Levelized Costs of Energy Analysis. New York: LAZARD. https://www.lazard.com/media/451881/lazards-levelized-cost-of-energy-version-150-vf.pdf.

Lévêque, François. 2014. *The Economics and Uncertainties of Nuclear Power*. Cambridge, MA, USA: Cambridge University Press.

Lordan-Perret, Rebecca, Robert D. Sloan, and Robert Rosner. 2021. “Decommissioning the U.S. Nuclear Fleet: Financial Assurance, Corporate Structures, and Bankruptcy.” *Energy Policy* 154 (July): 112280. https://doi.org/10.1016/j.enpol.2021.112280.

Lovins, Amory B. 2022. “US Nuclear Power: Status, Prospects, and Climate Implications.” *The Electricity Journal* 35 (4): 107122. https://doi.org/10.1016/j.tej.2022.107122.

Luderer, Gunnar, Silvia Madeddu, Leon Merfort, Falko Ueckerdt, Michaja Pehl, Robert Pietzcker, Marianna Rottoli, et al. 2021. “Impact of Declining Renewable Energy Costs on Electrification in Low-Emission Scenarios.” *Nature Energy*, November. https://doi.org/10.1038/s41560-021-00937-z.

Lynch, Arthur, Yannick Perez, Sophie Gabriel, and Gilles Mathonniere. 2022. “Nuclear Fleet Flexibility: Modeling and Impacts on Power Systems with Renewable Energy.” *Applied Energy* 314 (May): 118903. https://doi.org/10.1016/j.apenergy.2022.118903.

Nuttall, William J. 2022. *Nuclear Renaissance: Technologies and Policies for the Future of Nuclear Power*. Boca Raton: CRC Press. https://www.taylorfrancis.com/books/9781003038733.

Rothwell, Geoffrey. 2022. “Projected Electricity Costs in International Nuclear Power Markets.” *Energy Policy* 164 (May): 112905. https://doi.org/10.1016/j.enpol.2022.112905.

Schill, Wolf-Peter, and Alexander Zerrahn. 2020. “Flexible Electricity Use for Heating in Markets with Renewable Energy.” *Applied Energy* 266 (May): 114571. https://doi.org/10.1016/j.apenergy.2020.114571.

Schneider, Mycle, Antony Froggatt, Julie Hazemann, Christian von Hirschhausen, M.V. Ramana, Alexander James Wimmers, Michael Sailer, et al. 2022. “World Nuclear Industry Status Report 2022.” Paris: Mycle Schneider Consulting. https://www.worldnuclearreport.org/IMG/pdf/wnisr2022-hr.pdf.

Stirling, Andy, and Phil Johnstone. 2018. “A Global Picture of Industrial Interdependencies Between Civil and Military Nuclear Infrastructures.” SPRU Working Paper Series 2018-13 (August). Sussex, UK: University of Sussex. https://www.sussex.ac.uk/webteam/gateway/file.php?name=2018-13-swps-stirling-and-johnstone.pdf&site=25.

Wang, Dai, Matteo Muratori, Joshua Eichman, Max Wei, Samveg Saxena, and Cong Zhang. 2018. “Quantifying the Flexibility of Hydrogen Production Systems to Support Large-Scale

Renewable Energy Integration." *Journal of Power Sources* 399 (September): 383–91. https://doi.org/10.1016/j.jpowsour.2018.07.101.

Wealer, B., S. Bauer, C.v. Hirschhausen, C. Kemfert, and L. Göke. 2021. "Investing into Third Generation Nuclear Power Plants - Review of Recent Trends and Analysis of Future Investments Using Monte Carlo Simulation." *Renewable and Sustainable Energy Reviews* 143 (June): 110836. https://doi.org/10.1016/j.rser.2021.110836.

Zakeri, Behnam, Katsia Paulavets, Leonardo Barreto-Gomez, Luis Gomez Echeverri, Shonali Pachauri, Benigna Boza-Kiss, Caroline Zimm, et al. 2022. "Pandemic, War, and Global Energy Transitions." *Energies* 15 (17): 6114. https://doi.org/10.3390/en15176114.