The Potential of Small Modular Reactors to Provide System-Bearing Services in the Future Power Grid

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***Abstract*—The future power grid comprises large shares of inverter-based resources (IBRs) dominated by solar and wind power. As a result, the grid's resilience in terms of voltage and frequency regulation capabilities can be significantly reduced. To deal with this unsolved challenge, there is a potential for small modular reactors (SMRs) to provide, in addition to electricity and heat, system-bearing services that, at a reduced cost, can enable higher penetration of renewables. This paper shows that the alternative system-wide ancillary service cost for physical inertia and short-circuit capacity can be approximately $20/MWh when using synchronous condensers (SCs) to enable a 100 % renewable energy system. SMRs can avoid these additional system costs and, in addition, significantly increase the grid strength when compared to the use of SC devices. Moreover, it is shown that multiple SMR units instead of large nuclear power plants significantly reduce the needed frequency reserves.**

***Index Terms*—Turbogenerator, synchronous condenser, grid strength, short circuit level, voltage regulation, frequency regulation, inertial response, power grid, system costs.**

I. INTRODUCTION

Small modular reactors (SMRs) have recently received attention as a potential solution to play a significant role in the energy transition of global power and energy systems [1]–[3]. This also includes potential use in microgrids and standalone energy systems, as investigated by Abu Saleem *et al.* (2020) [4], Poudel *et al.* (2023) [5], and Huang *et al.* (2024) [6]. Recent research has also looked at the modeling of SMRs to investigate their behavior in power system dynamic stability studies. Poudel (2020) *et al.* developed a dynamic SMR model in Siemens PTI PSS/E [7]. Moreover, Rahman and Zhang (2024) investigated the integration of SMRs in the NREL-118 bus network with a focus on implementing flexibility constraints related to the phenomena of Xenon poisoning [8].

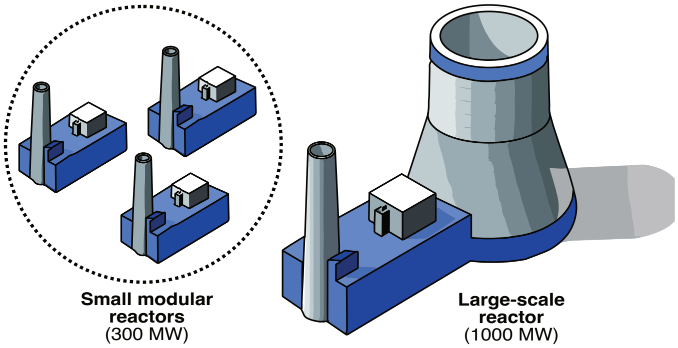

Fig. 1. Capacity comparison between a large, centralized nuclear power plant and a potentially decentralized cluster of small modular reactors (SMRs).

TABLE I
IAEA ELECTRICAL CAPACITY CLASSIFICATION [12]

Type	**Lower**	**Upper**
Microreactor (MR)	0 MW	10 MW
Small modular reactor (SMR)	10 MW	300 MW
Medium-scale reactor (MSR)	300 MW	700 MW
Large-scale reactor (LSR)	700 MW	–

An often overlooked aspect of nuclear power plants (NPPs) is their system-wide ancillary services that come as an added value to their power delivery. In low-load summer periods, NPPs can be scheduled to run on partial load to stabilize the grid [9]. This is the reason why, during the decommissioning of existing NPPs, the possibility of continued use of existing electrical infrastructure has been considered, and running the nuclear turbine-generator as a synchronous condenser (SC) [10]. However, large NPPs are in the gigawatt-scale, as highlighted in Fig. 1 and Table I, which cause an NPP outage from the grid to also create a need for frequency regulation services to be able to handle such an outage. From this perspective, multiple SMR units providing the same amount of power could reduce the amount of backup power needed to step in if one unit falls out (i.e., N-1 principle). The absence of SMRs and/or other NPPs in the future power grid could be represented by SCs [11], which has the same synchronous machine but lacks the contribution from nuclear energy and operates at no-load.

Available literature typically investigates grid-forming (GFM) inverters and SC for ensuring system-bearing services in the future power grid [13]–[15]. This paper, on the other hand, explores the potential of SMRs to provide grid strength, reactive power capability, and inertial response. Due to their smaller capacity compared to conventional NPPs, they can be deployed in a decentralized manner, departing from the centralized power system paradigm from the past. As highlighted in Fig. 2, SMR deployment can provide a myriad of system services locally at the grid level where the power is needed.

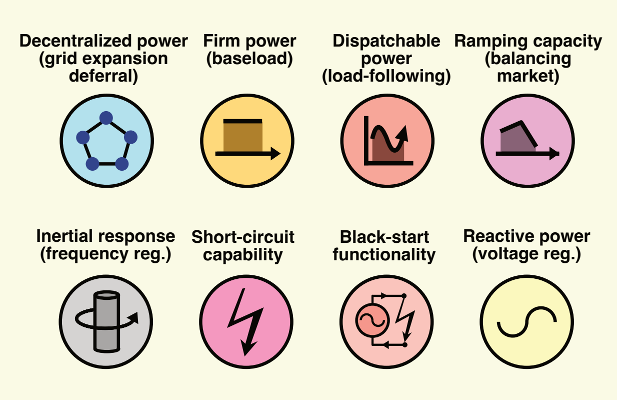

Fig. 2. Examples of system-bearing services that can be provided to the future power grid by small modular reactors.

The paper is organized as follows. Section II quantifies how SMRs contributes to power grid strength and voltage stability before Sections III presents their frequency regulation characteristics. Finally, the basics of synchronous condenser economics is presented in Section IV to give insights into the added value of SMRs in the future power system. Section V concludes the paper.

II. Power Grid Strength and Voltage Regulation

The short circuit level (SCL) of a power grid is a measure of its system strength, where the key contributors are its grid-forming synchronous generators. A high SCL means that the short circuit current that is achievable at the point of connection (POC) is high relative to the nominal current. A grid with an SCL of 3 or higher at the POC is considered a strong grid [16]. The importance of these properties is related to their overcurrent abilities during faults, which are essential for power system operations, such as grid protection devices, black-start functionality, restoration services, and transient voltage stability. For inverter-based resources (IBRs) like solar and wind power facilities, the overcurrent ability is about 1.1–1.2 pu, implying that the grid strength of a 100 % inverter-based grid can be very weak [17]. SCs or alternative solutions will be needed if the IBRs are not mixed together with synchronous production units like SMRs that have these system-bearing functionalities in-house and can provide the bulk of stability and reliability as an added value to the system. Another research paradigm is the use of grid-forming (GFM) IBRs in regions with high penetration of IBRs beyond 70 % instantaneous share [13]. Li, Nie, and Wang (2022) argue for co-locating IBRs with SCs to solve the overcurrent problem [14]. Similarly, Kenyon *et al.* (2020) proposed an SC and an IBR as a GFM pair [15]. From this perspective, SMRs could be considered an alternative to SCs with even better functionalities to complement IBRs, as explored herein.

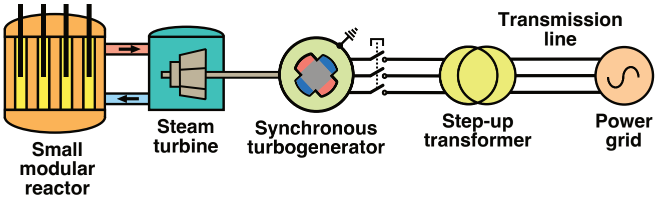

Fig. 3. Three-phase diagram of an SMR connected to a power grid.

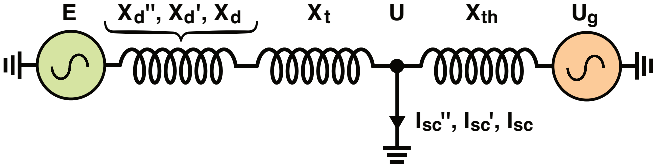

Fig. 4. Single-line diagram of an SMR during a grid fault at the POC.

TABLE II

Representative Standard Parameter Values for a Generic Turbogenerator [18], [19]

Parameter	**Symbol**	**Lower**	**Upper**
Synchronous reactance	X_d	1.80 pu	2.00 pu
Transient reactance	X'_d	0.22 pu	0.30 pu
Subtransient reactance	X''_d	0.17 pu	0.25 pu
External reactance	X_t	0.10 pu	0.15 pu
Total inertia	H	6.50 s	8.70 s

Fig. 3 depicts a single SMR connected to an interconnected power grid through a front-end synchronous turbogenerator and a step-up transformer, providing both active and reactive power. To analyze the SMR's contribution to the power grid's strength, Fig. 4 presents the same SMR through its turbogenerator characteristic in a single-line diagram with a three-phase short circuit at the POC. Eq. (1) expresses the internal phasor voltage ($\mathbf{E}$) of the SMR's turbogenerator relative to the terminal voltage (U) and assuming a round, cylindrical rotor with non-salient poles, which simplifies the electrical analysis. The internal voltage prior to the short circuit can be used to estimate the subtransient, transient, and stationary short circuit currents (I''_{sc}, I'_{sc}, and I_{sc}) expressed in eq. (2). Representative turbogenerator parameter values are provided in Table II.

$$\mathbf{E} = U + \mathbf{j}(X_d + X_t) I \mathbf{e}^{-\mathbf{j}\varphi} \tag{1}$$

$$I''_{sc} = \frac{|\mathbf{E}|}{X''_d + X_t}, \quad I'_{sc} = \frac{|\mathbf{E}|}{X'_d + X_t}, \quad I_{sc} = \frac{|\mathbf{E}|}{X_d + X_t} \tag{2}$$

The SCL of a turbogenerator is related to its loading condition prior to faults. Fig. 5 depicts the capability diagram of a representative turbogenerator, including isoefficiency curves, with a power level compatible with SMRs. We can observe that the reactive power consumption capability on the left-hand side of the diagram is not as good as its supply of reactive power. This is generally the case for turbogenerators, which makes them slightly less favorable than salient-pole hydrogenerators in terms of reactive power capability. Nevertheless, different from large-scale hydropower, SMRs are like large NPPs baseload electricity sources with a low marginal price throughout the year and a high capacity factor. This implies that SMR's active power output will be high for most of the year, and their reactive power support will be readily available

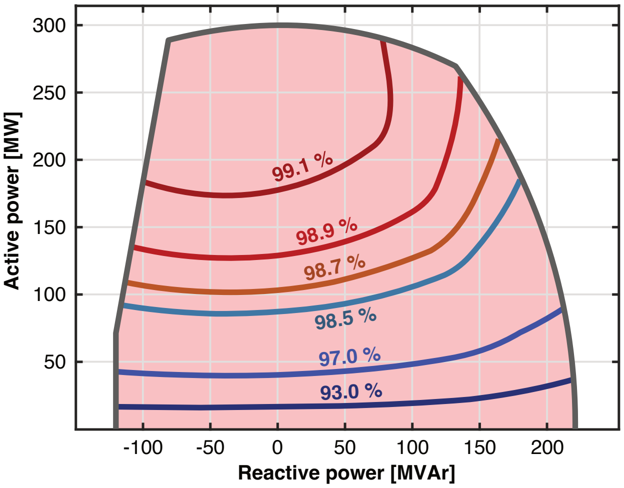

Fig. 5. Capability diagram of the Siemens SGen5-2000P 300 MVA turbogenerator compatible with small modular reactors (SMRs). An isoefficiency map is indicated, describing the efficiency of different operating points [20].

at a stable, low marginal cost. Their reactive power output can vary more widely than the active power, depending on the voltage conditions in the interconnected power grid.

The delivery of active power (P) and reactive power (Q) is determined by the electrical angle (φ) between the terminal voltage (U) and the supplied current (I), according to eqs. (3) and (4) formulated in per unit.

$$P = UI\cos(\varphi) \quad (3) \qquad Q = UI\sin(\varphi) \quad (4)$$

By forcing the active power (P) in eq. (3) to be equal to the maximum power output (P_{max}) of the SMR, the current loading is given by eq. (5).

$$I = \frac{P_{max}}{U\cos(\varphi)} \quad (5)$$

Eq. (5) is inserted into eq. (4) to establish eq. (6).

$$\frac{Q}{P_{max}} = \tan(\varphi) \quad (6)$$

If the turbogenerator is operating in SC condition, the reactive power is given by eq. (7), assuming that the current (I) is perpendicular to the terminal voltage (U).

$$Q = U\underbrace{\frac{E-U}{X_d+X_t}}_{I} \quad (7)$$

Eq. (7) can be expressed with respect to the internal voltage (E) under SC condition, according to eq. (8).

$$E = U + \frac{Q}{U}(X_d + X_t) \quad (8)$$

Fig. 6 plots the internal voltages of the turbogenerator under both SMR and SC operation. It is evident that the internal voltage is significantly weaker as an SC, especially when reactive power is consumed from the grid. This negatively impacts the SCL, as shown in Fig. 7. The SMR can provide a subtransient SCL of six to nine times the nominal rating at nominal conditions and can compensate for IBR's weak overcurrent capability.

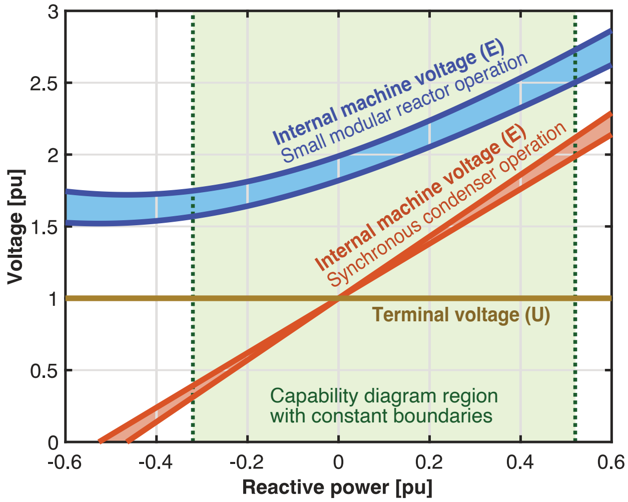

Fig. 6. Comparison of the internal machine voltage (E) under both SMR and SC operation calculated from eqs. (1) and (8), respectively. Upper and lower representative parameter values in Table II are used as input to the analysis. SMR operation assumes P_{max} = 0.8 pu and capability diagram boundaries are fixed to Q/P_{max} = 0.65 pu and Q/P_{max} = -0.4 pu [19].

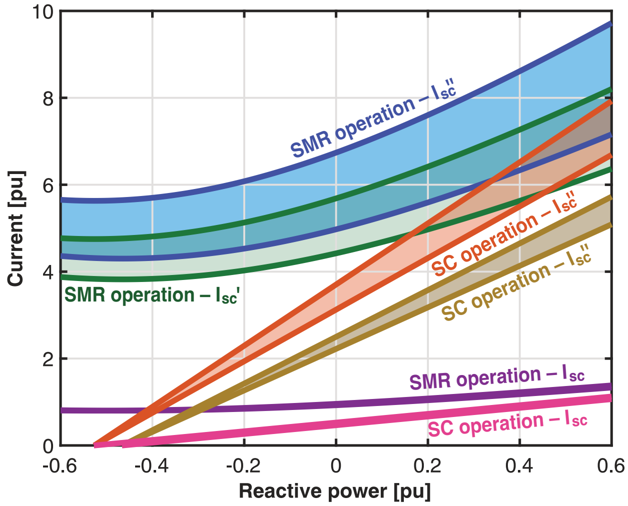

Fig. 7. Comparison of the short circuit currents (I''_{sc}, I'_{sc}, and I_{sc}) under both SMR and SC operation calculated from eq. (7) with the internal machine voltages calculated in Fig. 6.

A typical rated power factor of a turbogenerator is 0.8, yielding a reactive power of 0.6 pu to make the apparent power unity. This implies that the maximum power output of the SMR (P_{max}) will be 0.8 pu. As a result, the reactive-to-active power ratio (Q/P_{max}) of 0.75 but, in reality, it can be lower, e.g., 0.65 [19], yielding a reactive power capability that is 65 % of the SMRs' electrical rating. Due to stability constraints, the capability of consuming reactive power is lower, e.g., Q/P_{max} = -0.4 [19]. The required reactive power envelope depends on the grid code [21].

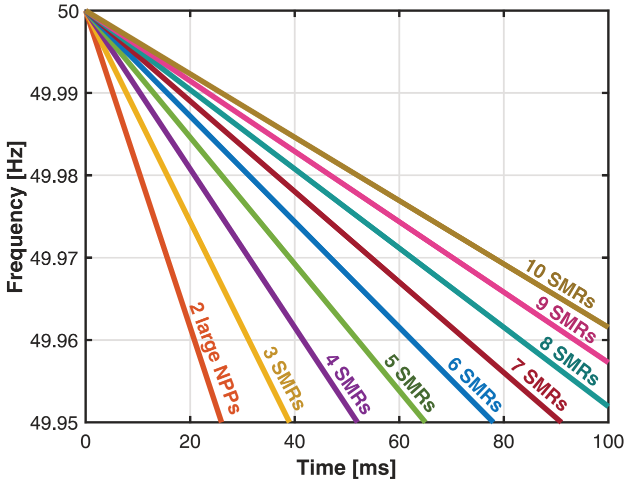

Fig. 8. Approximation of the RoCoF due to an SMR outage in an SMR-dominated, 50 Hz power system using eq. (9) and assuming an inertia constant (H) of 6.5 s, consistent with the low case in Table II.

III. Inertial Response and Frequency Regulation

Another benefit of SMRs and SCs is their ability to store short-term rotational energy to stabilize the frequency of the power grid. According to the swing equation, the initial rate of change of frequency (RoCoF) in a power system can be approximated using eq. (9), where f_0 is the initial electrical frequency, H is the inertia constant, P_g is the power generated, P_l is the power consumed, and S_b is base apparent power.

$$\mathrm{RoCoF} = \frac{\mathrm{df}}{\mathrm{dt}} \approx \frac{\mathrm{f_0}}{\mathrm{2H}} \cdot \frac{\mathrm{P_g - P_l}}{\mathrm{S_b}} \tag{9}$$

An illustrative example of eq. (9) is shown in Fig. 8, where a stylized SMR-dominated power system is assumed. As the power system is composed of an increasing number of SMR units relative to the proportion of the whole system, the initial RoCoF is significantly reduced, reducing the need for additional system inertia and fast frequency reserves (FFR) to limit the frequency nadir. The potential of reduced frequency regulation services needed with SMRs is indirectly a system-bearing service provided to the grid.

IV. Synchronous Condenser Economics

As explored in the earlier sections, SCs have properties, such as voltage regulation and inertial response, which are similar to those of SMRs in terms of their system-bearing services. Nevertheless, SMRs provide superior grid strength when it comes to short-circuit power. Moreover, the inertia constant (H) of off-the-shelf SCs is 5–6 s [22], which is slightly lower than the inertia of turbogenerators suitable for SMRs with an inertia constant of 6-9 s [18], [19]. Although SCs can aid in black-start situations, they cannot independently provide this service as a synchronous generator driven by SMRs. Table III compares the system-bearing services of SMRs configured with synchronous generators, SCs, static var compensators (STATCOMs), and IBRs.

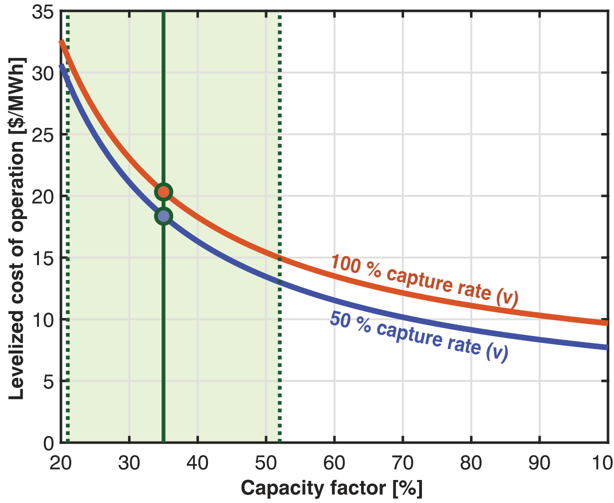

Fig. 9. Levelized cost of operation (LCOO) of SC facilities as a function of capacity factor and capture rate of wholesale electricity price. Calculations are based on eq. (10) using economic model parameters in Table IV.

TABLE III
Comparison of System-Bearing Services [23]

Service	**SMRs**	**SCs**	**STATCOMs**	**IBRs**
Physical inertia	High	Moderate	No	Virtual
Reactive power	Yes	Yes	Yes	Yes
Voltage regulation	Yes	Yes	Yes	Yes
Short-circuit current	Yes	Moderate	Limited	Limited
Overload capacity	High	High	Limited	Moderate
Black-start capability	Yes	Limited	No	Limited
Fault ride-through	High	High	Moderate	High
Harmonic filtering	Limited	Limited	Yes	Yes

To estimate the economic value of SMR's contribution to system-bearing services, the economics of SCs could provide an alternative cost. Power electronic devices like STATCOMs have no moving parts and, thus, lower expected maintenance costs but provide fewer ancillary services than SCs. They are, therefore, not included in the economic analysis herein but could be included in future research. For simplification, we assume that an additional SC kVA of SC is needed for every kW of IBR. In existing power systems, synchronous production has a minimal share of 30 % when renewables are in surplus. However, as shown in this paper, SCs have lower SCL capabilities than SMRs. We, therefore, assume a 50 %-50 % share of SC vs. IBR capacity. Nevertheless, this assumption is in practice depending on grid-specific requirements.

Table IV presents the parameters used to evaluate SC economics. These are inserted into eq. (10) to calculate the SC's levelized cost of operation (LCOO), where t = 8765.8 h.

$$\mathrm{LCOO} = \frac{c + \sum_{i=0}^{n-1} \frac{\sigma vpkt + dc}{(1+r)^i}}{\sum_{i=0}^{n-1} \frac{(1-\sigma)kt}{(1+r)^i}} \tag{10}$$

Fig. (9) presents the evaluated LCOO based on the given model parameters. In general, the LCOO is more sensitive to the SC capacity factor than to the captured electricity price to supply the electricity needed to overcome the losses in the

TABLE IV

SYNCHRONOUS CONDENSER ECONOMIC MODEL PARAMETERS

Parameter	**Symbol**	**Value**	**Ref.**
Capital expenditure (CAPEX) in 2024 \$	c	$\$427/\mathrm{kVA}$	[24]
Operational expenditure (OPEX)	d	$2\,\%$	[25]
Capacity factor (utilization rate)	k	21–52 %	[26]
Power losses relative to nominal rating	σ	$3\,\%$	[27]
Wholesale electricity price	p	$\$127.2/\mathrm{MWh}$	[28]
Capture rate of electricity price	v	50–110 %	[29]
Weighted average cost of capital (WACC)	r	$9.7\,\%$	[30]
Expected lifetime in number of years	n	30	[24]

SC. This is because the power losses are low relative to the SC power capability. Notably, this relationship can encourage potential investments in SCs, as the cost associated with power loss costs will decrease with lower capture rates, which is more likely to happen in periods with ample IBRs on the grid, thereby slightly improving SC economics. For an average scenario of the expected SC utilization rate of$35\,\%$, the LCOO is around $\$20/\mathrm{MWh}$, which serves as an estimate of the system-bearing value an SMR, or any synchronous generation unit, would have in the same system if replaced by the SC. However, further economic measures are needed to assess the value of the investment accurately, considering the uncertainty in the future activated volume of ancillary services. Currently, GFM inverters do not influence the economic evaluation of SMRs' ancillary service provision in the short term, as standalone IBRs would depend on support from SCs [15].

V. CONCLUSION

This paper has shown that small modular reactors (SMRs) can reduce system-wide ancillary service costs by approximately \$20/MWh in the future power grid and significantly improve the short circuit level (SCL) of the power grid when compared to synchronous condensers (SCs). Although this may rather not be the primary reason for deploying SMRs, these findings emphasize their additional benefits to contribute together with inverter-based resources like solar and wind in a future decarbonized power grid. Nevertheless, SMRs are expected to be commercially competitive within the next decade, which inevitably will limit their role in the short term, where other options need to be considered in parallel.

REFERENCES

[1] D. Michaelson and J. Jiang, "Integration of small modular reactors into renewable energy-based standalone microgrids: An energy management perspective," *IEEE Power Energy Mag.*, vol. 20, no. 2, pp. 57–63, 2022.

[2] J. K. Nøland, M. Hjelmeland, L. B. Tjernberg, and C. Hartmann, "The race to realize small modular reactors: Rapid deployment of clean dispatchable energy sources," *IEEE Power Energy Mag.*, vol. 22, no. 3, pp. 90–103, 2024.

[3] J. K. Nøland, M. Hjelmeland, C. Hartmann, L. B. Tjernberg, and M. Korpås, "Overview of Small Modular and Advanced Nuclear Reactors and Their Role in the Energy Transition," *IEEE TechRxiv*, 2024.

[4] R. Abu Saleem, J. Kelly, T. Rousan, and P. W. Sauer, "Issues in the use of small modular reactors in microgrids," *IEEE Trans. Power Delivery*, vol. 35, no. 3, pp. 1230–1236, 2020.

[5] B. Poudel, T. R. McJunkin, N. Kang, J. T. Reilly, R. Guerrero, and M. Stadler, "Small reactors in microgrids: Technology modeling and selection," Idaho National Laboratory (INL), Idaho Falls, ID (United States), Tech. Rep., 2023.

[6] M. Huang, X. Cui, N. Zhang, M. Jia, and Y. Wang, "Optimal planning of standalone net-zero energy systems with small modular reactors," *IEEE Trans. Smart Grid*, pp. 1–1, 2024.

[7] B. Poudel, K. Joshi, and R. Gokaraju, "A dynamic model of small modular reactor based nuclear plant for power system studies," *IEEE Trans. Energy Convers.*, vol. 35, no. 2, pp. 977–985, 2020.

[8] J. Rahman and J. Zhang, "Steady-state modeling of small modular reactors for multi-timescale power system operations with temporally coupled sub-models," *IEEE Trans. Power Syst.*, pp. 1–13, 2024.

[9] "Ringhals 1 stöttar elnätet i sommar," *Vattenfall*, 2020. [Online]. Available: https://group.vattenfall.com/se/nyheter-och-press/nyheter/2020/ringhals-1-stottar-elnatet-i-sommar

[10] V. Gliniewicz, "Decommissioned Nuclear Power Plant as System Services Providers, *Energiforsk*, 2017:348." [Online]. Available: https://energiforsk.se/en/programmes/nuclear-power-outlook-and-technology-development/rapport/decommissioned-nuclear-power-plant-as-system-services-providers/

[11] P. E. Marken, A. C. Depoian, J. Skliutas, and M. Verrier, "Modern synchronous condenser performance considerations," in *Proc. IEEE Power Energy Soc. Gen. Meet.*, 2011, pp. 1–5.

[12] J. Liou, "What are Small Modular Reactors (SMRs)?" *International Atomic Energy Agency (IAEA)*, 2023. [Online]. Available: https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs

[13] N. Modi, M. V. Escudero, K. Aramaki, X. Zhou, and P. Partinen, "High inverter-based resource integration: The experience of five system operators," *IEEE Power Energy Mag.*, vol. 22, no. 2, pp. 78–88, 2024.

[14] H. Li, C. Nie, and F. Wang, "Grid strengthening IBR: An inverter-based resource enhanced by a co-located synchronous condenser for high overcurrent capability," *IEEE Open J. Power Electron.*, vol. 3, pp. 535–548, 2022.

[15] R. W. Kenyon, A. Hoke, J. Tan, B. Kroposki, and B.-M. Hodge, "Grid-Following Inverters and Synchronous Condensers: A Grid-Forming Pair?" *National Renewable Energy Laboratory (NREL)*, 2020.

[16] C. Henderson, A. Egea-Alvarez, T. Kneuppel, G. Yang, and L. Xu, "Grid strength impedance metric: An alternative to SCR for evaluating system strength in converter dominated systems," *IEEE Trans. Power Delivery*, vol. 39, no. 1, pp. 386–396, 2024.

[17] N. Nimpitiwan, G. T. Heydt, R. Ayyanar, and S. Suryanarayanan, "Fault current contribution from synchronous machine and inverter based distributed generators," *IEEE Trans. Power Delivery*, vol. 22, no. 1, pp. 634–641, 2007.

[18] C.-E. Stephan and Z. Baba, "Specifying a turbogenerator's electrical parameters guided by standards and grid codes," in *Proc. IEEE Int. Electr. Mach. Drives Conf.*, 2001, pp. 63–68.

[19] L. Rouco, K. Chan, J. Oesterheld, and S. Keller, "Recent evolution of european grid code requirements and its impact on turbogenerator design," in *Proc. IEEE Power and Energy Soc. Gen. Meet.*, 2012.

[20] M. Baca and A. Joswig, "Innovative generator products for high operational flexibility at low product, installation and operating costs," *Siemens*, 2017.

[21] "Requirements for Generators (RfG)," *ENTSO-E*, 2016.

[22] C. Payerl, "Introduction to ABB Synchronous Condenser offering: A solution to improve grid strength," *ABB*, 2020.

[23] H. Jain, G.-S. Seo, E. Lockhart, V. Gevorgian, and B. Kroposki, "Blackstart of power grids with inverter-based resources," in *Proc. IEEE Power & Energy Soc. Gen. Meet.*, 2020, pp. 1–5.

[24] "Economic life for ElectraNet synchronous condensers," *ElectraNet*, 2019. [Online]. Available: https://www.aer.gov.au/system/files/GHD%20Advisory%20-%20MGSS%20Contingent%20Project%20-%20Economic%20Life%20Advice%20-%2028%20June%202019.pdf

[25] R. West, "Synchronous condensers: the economics?" *Thunder Said Energy*. [Online]. Available: https://thundersaidenergy.com/downloads/synchronous-condensers-the-economics/

[26] "Wind Energy Factsheet," *Pub. No. CSS07-09, Centre for Sustainable Systems, University of Michigan*, 2023.

[27] L. Richard, Nahid-Al-Masood, T. K. Saha, W. Tushar, and H. Gu, "Optimal allocation of synchronous condensers in wind dominated power grids," *IEEE Access*, vol. 8, pp. 45 400–45 410, 2020.

[28] B. Alves, "Average retail electricity prices in the United States from 1990 to 2023. Statista," 2024.

[29] L. Hirth, "The market value of variable renewables: The effect of solar wind power variability on their relative price," *Energy Econ.*, vol. 38, pp. 218–236, 2013.

[30] "2023 Levelized Cost Of Energy+," *Lazard*, 2023.