Article

Next Generation Nuclear Power for Non-Power Applications in the Middle-East Region

Joseph D. Smith [1,*], Kyle L. Buchheit[2], Haider Al-Rubaye[3] , Shoaib Usman[4], Yishu Zhou [5] and Greg Gelles [6]

1 Chem and Biochem Eng, Laufer Endowed Energy Chair, Missouri Univ of Sci and Tech, USA; smith-jose@mst.edu
2 KeyLogic Systems, Morgantown, WV, United States (KBuchheit@Keylogic.com)
3 Chem and Biochem Eng, Missouri Univ of Sci and Tech, USA, haa9r6@mst.edu
4 Nuclear Engineering, Missouri Univ of Sci and Tech, United States (usmans@mst.edu)
5 Economics., Assistant Prof, Missouri Univ of Sci and Tech, USA, yishuz@mst.edu
6 Economics., Chancellor's Prof, Missouri Univ of Sci and Tech, USA, gelles@mst.edu
* Correspondence: smithjose@mst.edu

Abstract: Small modular reactors (SMR) (<300 MW) offer a potentially attractive nuclear energy option for the middle-east region (MER). Currently, the MER uses a significant amount of fossil fuel to process heat applications such as water desalination and in petroleum refineries and chemical plants, besides generating electricity. SMR technologies represent an opportunity to meet future energy demand in the MER. This paper discusses issues related to the future development and use of SMR technology in nuclear-renewable hybrid energy systems for application in the middle east. SMRs have also been examined as part of a resilient hybrid energy system that combines nuclear energy with renewable energy and traditional fossil energy to produce chemicals, fuels, and electricity. This paper presents the results of a techno-economic analysis of a Nuclear-Renewable-Conventional Hybrid Energy System. The paper concludes that SMR technology will be an essential feature of future hybrid energy systems for the MER.

Keywords: nuclear energy; renewable energy; fossil energy; small modular reactors; resilience; hybrid energy

1. Introduction

SMRs can provide heat for desalinating seawater, converting natural gas to liquid transportation fuels, and hydrogen production. SMRs represent a new generation of smaller reactors when large traditional nuclear plants are not feasible. Several SMR designs have been proposed, but only a few have been installed. SMR technologies have been evaluated according to 1) water usage, 2) safety considerations, 3) demonstrated technology readiness, and 4) passive safety features related to operation after a loss of coolant accident. SMR's inherent passive safety features and the ability to manufacture reactor modules in a fabrication plant with modules shipped to the plant site for subsequent installation make SMR technology attractive for application in the MER. For these reasons, SMR technology is expected to be part of the energy future for the MER.

Traditional "light-water" nuclear reactors are typically used only to generate electric power. Over 450 nuclear reactors are operated in France, the United States, China, Russia, and many other countries, as shown in **Error! Reference source not found.** and

. Recent work at the Idaho National Laboratory has focused on developing nuclear hybrid systems that can meet industrial demands for desalinating seawater, converting natural gas to valuable liquid fuels, and hydrogen production for crude upgrading [Aumeier et al., 2010, Braggs-Sitton et al., 2020]. Nuclear plant suppliers have also been actively developing new small modular nuclear reactor designs for applications where large plants are not optimal or too expensive to consider. Several SMR designs have been proposed (see Table 1). SMRs are inherently safe, have power generation capacities <300

MWe, allow for modular production in fabrication plants and allow shipment of modules to the plant site for subsequent assembly.

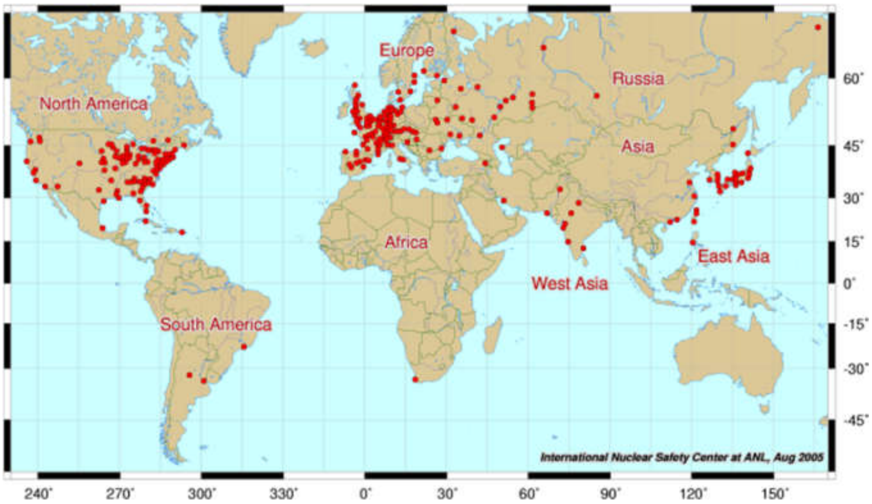

Figure 1. Worldwide location of operating nuclear power plants in 2005 (International Nuclear Safety Center, operated by USDOE). [Bonavigo and De Salve, 2011, Figure 1].

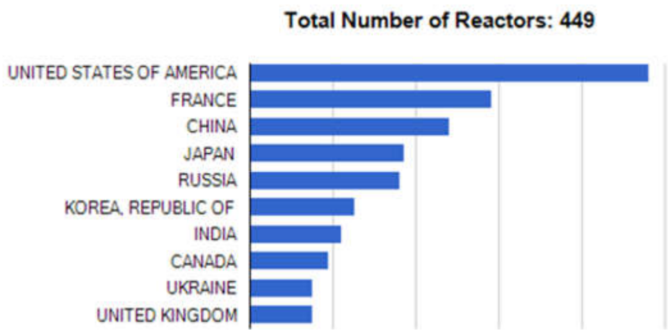

Figure 2. Number of operating nuclear power plants in 2019 with top 10 countries listed.[1].

Table 1. Available SMR designs for application in use in MER.

Name	Capacity	Type	Developer
Westinghouse SMR	200 MWe	PWR	Westinghouse, USA
mPower	150-180 MWe	PWR	Babcock & Wilcox + Bechtel, USA
NuScale	45 MWe	PWR	NuScale Power + Fluor, USA
Prism	311 MWe	FNR	GE-Hitachi, USA
SMR-160	160 MWe	PWR	Holtec, USA
EM2	240 MWe	HTR	General Atomics (USA)
Gen4 module	25 MWe	FNR	Gen4 (Hyperion), USA
SC-HTGR (Antares)	250 MWe	HTR	Areva, France
SMART	100 MWe	PWR	KAERI, South Korea
CAREM	27-100 MWe	PWR	CNEA & INVAP, Argentina
SVBR-100	100 MWe	FNR	AKME-engineering (Rosatom/En+), Russia
KLT-40S	35 MWe	PWR	OKBM, Russia
BREST	300 MWe	FNR	RDIPE, Russia
VK-300	300 MWe	BWR	Atomenergoproekt, Russia
ACP100	100 MWe	PWR	CNNC & Guodian, China
HTR-PM	2x105 MWe	HTR	INET & Huaneng, China
FUJI	100 MWe	MSR	ITHMSO, Japan-Russia-USA

Further "modular fabrication" facilitates significantly better quality control which drives fabrication costs lower and accelerates plant construction. In addition, some SMR designs use air cooling instead of water cooling, which makes them especially attractive

[1] Information available at https://pris.iaea.org/PRIS/WorldStatistics/OperationalReactorsByCountry.aspx

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 May 2022 doi:10.20944/preprints202205.0406.v1

for use in the MER. These features make SMRs an attractive alternative to supply both electric power and process heat to the petrochemical industry in the MER.

The International Atomic Energy Agency (IAEA) has identified key SMR evaluation issues, including economics, risk and safety, and proliferation resistance. Using these issues, countries in the MER have begun exploring SMR research to address the emerging opportunity to apply this technology in the MER.

Currently, countries in the MER rely mainly on fossil fuels for refining and chemical production. To fully maximize the benefits of new SMRs, they should be combined with conventional nuclear power plants (NPPs) to support regions with growing energy demand. K.A.CARE[2] has previously ranked available SMR technologies, including standard light-water designs plus other advanced technologies with higher thermal efficiency, to support the Kingdom of Saudi Arabia's (KSA) in developing and commercializing SMR production in the MER.

This study considered SMR technology for application in hybrid nuclear-renewable-conventional energy systems. This study also examined the consideration of the technology readiness, design viability, and development plan for SMR designs.

2. Nuclear-Renewable Energy Systems

One of the most critical challenges countries will face over the next thirty years will be related to energy security. Economic activity is directly tied to a country having a secure low-cost energy supply. As shown in the image below, electric power use (i.e., city lights) shows regions of the world with growing economies (see Figure 3).

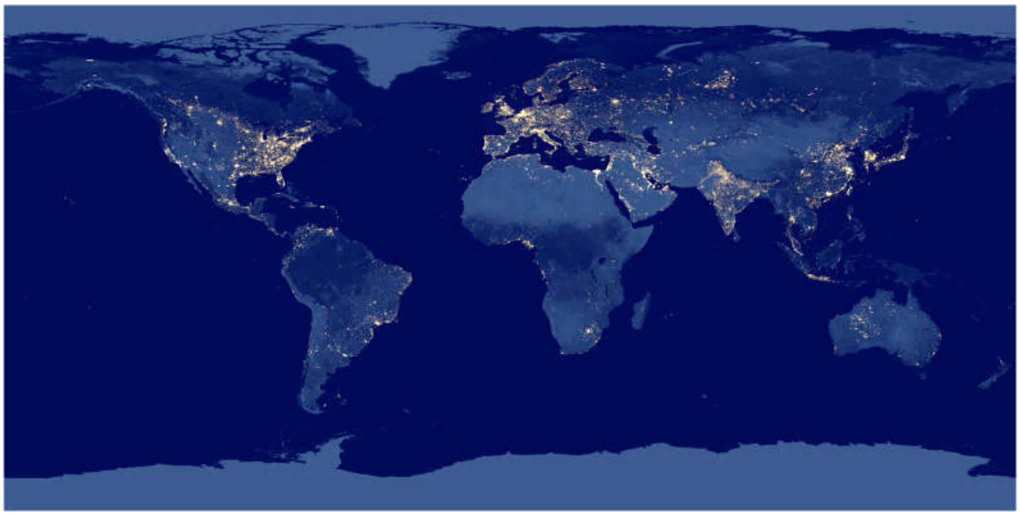

Figure 3. City lights seen from space over six months[3].

The current world population is approximately 7.8 billion people. Over 3 billion people live in China and India alone (see Figure 4). The MER (Western Asia) currently has 283 million people, with over 84 million living in Turkey, 40 million in Iraq, 35 million in Saudi Arabia, and 30 million in Yemen (see Figure 5). This region has a population growth rate of 1.65%, increasing economic activity, and rising energy demand. Countries in the MER have a limited amount of fossil fuels (i.e., oil and gas). They are now considering ways to develop more sustainable renewable energy resources such as wind and solar power. As power demand increases, the threat to our climate increases when non-sustainable energy is used. As these non-sustainable energy reserves become more scarce,

[2] K.A.CARE (King Abdulla City of Atomic and Renewable Energy) is focused on developing next generation energy technology for the Kingdome of Saudi Arabia.

[3] Downloaded from https://earthobservatory.nasa.gov/images/79765/night-lights-2012-map

the threat of war fought to control essential energy resources also increases. Thus, finding ways to meet increasing electric power demand in a sustainable, resilient way is critically important and represents a "grand challenge" for this generation.

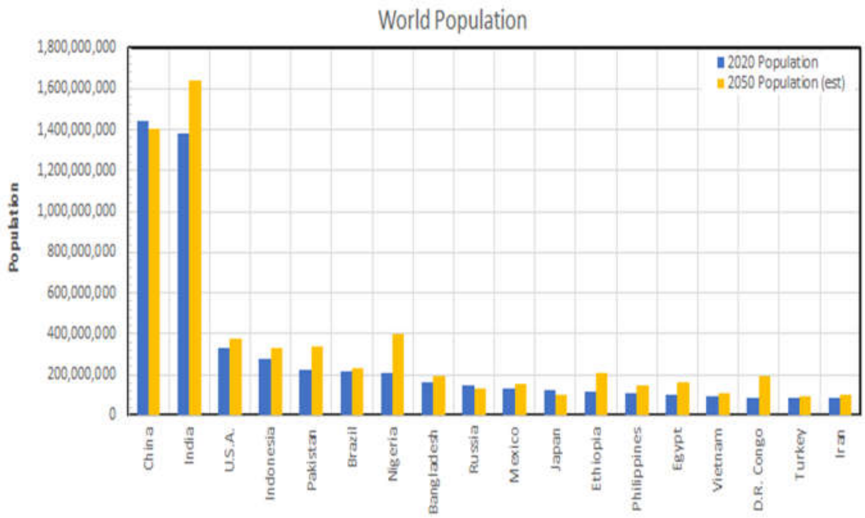

Figure 4. World Population (2020) vs. Est. World Population (2050).

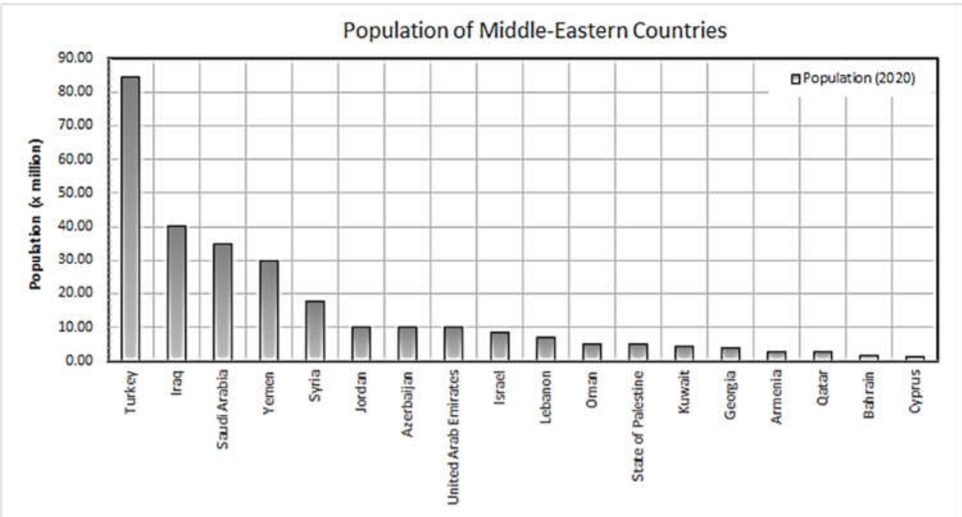

Figure 5. Middle-Eastern Country Population (2020).

To help the MER transition from high carbon-intense energy resources (e.g., fossil fuels) to reduce its carbon footprint will require nuclear energy. The best way to accomplish this is using Nuclear-Renewable Hybrid Energy, as discussed by Braggs-Sitton and co-workers at the Idaho National Laboratory [Bragg-Sitton et al., 2020]. The concept combines multiple renewable energy resources (i.e., wind and solar) available in the MER with traditional fossil fuels (i.e., gas and coal) and nuclear energy, as shown in **Error! Reference source not found.**.

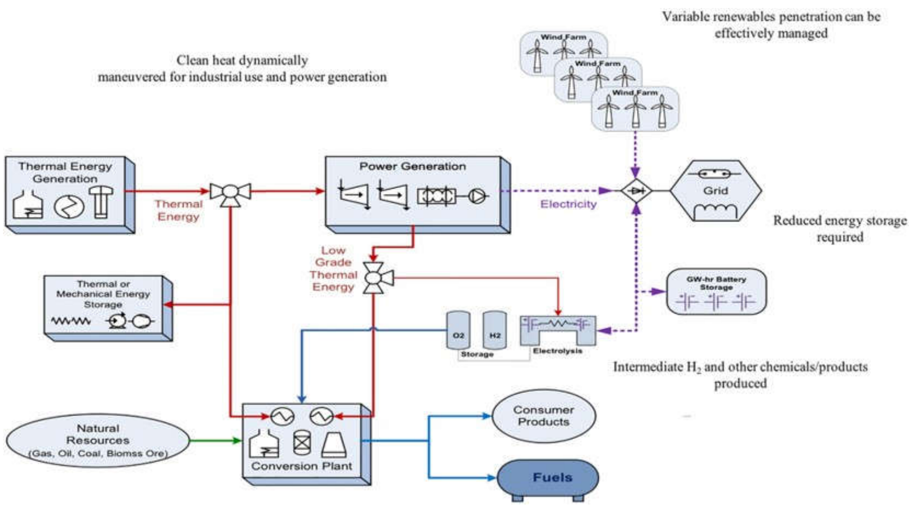

Figure 6. Nuclear-Renewable Hybrid system [Bragg-Sitton et al., 2020].

Previous work by the author examined a coal-wind-nuclear hybrid system that used a pressurized circulating fluid bed (PCFB) reactor to burn coal with oxygenated combustion air produced in a high-temperature co-electrolysis (HTCE) unit using waste heat from an SMR together with electric power from wind machines or solar panels. The HTCE produced syngas together with oxygen-rich sweep gas. The syngas was fed to a fischer-tropse catalytic reactor to produce chemicals and/or transportation fuels (see Figure 7).

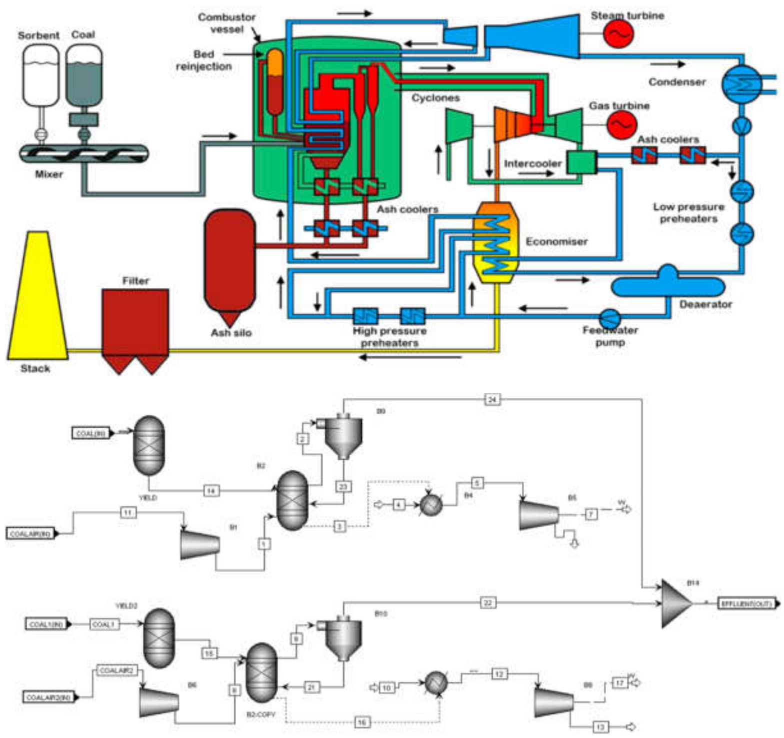

Figure 7. High-Pressure-Circulating-Fluid-Bed combustor to produce CO2 for High-Temperature Co-Electrolysis Unit and Electric power [Buchheit et al., 2016].

The dynamic model used to analyze this hybrid energy system is shown in Figure 8. The process model allowed wind (or solar) energy variability combined with an active load profile to capture the extensive range of time constants associated with system dynamics. Using the model, the Nuclear-Renewable-Convention Energy System was analyzed, and results were used to examine the system's economics.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 31 May 2022 doi:10.20944/preprints202205.0406.v1

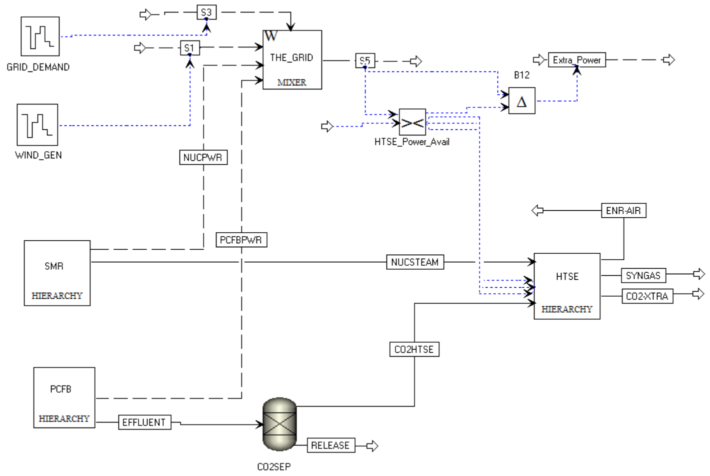

Figure 8. Coal-Wind-Nuclear hybrid energy system to produce low-carbon electric power plus chemicals or fuels [Buchheit et al., 2016].

Using the dynamic process model, various configurations of the proposed hybrid system were examined. The analysis included the effects of a variable load combined with intermittent energy resources. The economic study showed how hybridizing multiple energy resources impacted system costs with and without a carbon tax [Buchheit, 2015]. Results illustrate the overall benefit of combining nuclear energy with renewable and conventional energy (see Table 2) with and without a carbon tax. This analysis can perform a complete life cycle analysis of a proposed hybrid energy system using SMR technology with fossil and renewable energy.

Table 2. Cost Analysis of Coal-Wind-Nuclear Hybrid Energy System [Buchheit, 2015].

Cost Source	Conventional Coal (Reference Case)	Hybrid Energy (No HTSE)	Base Hybrid System (Levelized Cost)	10% Hybrid (No HTSE)	10% Hybrid
Conventional Coal	$336.40	-	-	-	-
PCFB (Advanced Coal)	-	$198.80	$198.80	$68.00	$68.00
Advanced Nuclear	-	$176.00	$176.00	$46.40	$46.40
Wind	$10.90	$10,871.00	$10.90	$10.90	$10.90
Advanced Combustion Turbine	$16.80	$16.80	$16.80	$16.80	$16.80
Solid Oxide Fuel Cell	-	-	$21.00	-	$21.00
Hybridized Capital Cost	-	-	-	$234.30	$234.30
$15/Metric ton CO2	$678.90	$330.40	$303.60	$330.40	$303.60
$30/Metric ton CO2	$1,357.80	$660.70	$607.10	$660.70	$607.10
Total Cost	$364.10	$402.40	$423.40	$376.40	$397.40
Total Cost + $15 tax	$1,043.00	$732.80	$727.00	$706.70	$701.00
Total Cost + $30 tax	$1,721.90	$1,063.10	$1,030.60	$1,037.10	$1,004.50

3. Discussion

A current grand challenge society must solve is finding ways to provide clean, sustainable energy to a growing population in developing parts of the world with minimum impact on the climate. One option is combining Small Modular Nuclear reactor technology with renewable wind/solar energy and conventional gas/coal fossil energy to generate electric power with minimum carbon emissions and other products, including chemicals and transportation fuels. Ongoing work aimed at developing advanced Nuclear-Renewable Hybrid energy systems by the US Department of Energy, together with academic research by the authors, has investigated various hybrid system configurations that have been shown to have superior economic performance with and without a carbon tax. This work aims to develop a new generation of energy technology for the middle-east region, which can help alleviate energy poverty and allow the expanding population with its associated increased economic activity to prosper. Hybrid energy systems such as the one presented in this paper represent one solution to society's current grand challenge related to providing secure, resilient energy to the world that must be solved to alleviate energy poverty and reduce the threat of future energy wars.

Author Contributions: Conceptualization, J.S., S.U. and G.G.; methodology, J.S., K.B., H. A.; software, J.S., H.A. and K.B; validation, J.S., K.B., H.A., G.G., and Y.Z..; formal analysis, J.S., and K.B. Investigation, J.S., K.B. and H.A., resources, J.S., G.G. and Y.Z.; data curation, J.S.; writing—original draft preparation, J.S.; writing—review and editing, Y.Z. and J.S.; visualization, J.S., K.B, and H.A.; supervision, J.S.; project administration, J.S.; funding acquisition, J.S.; All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Aumeier, S., Cherry, R., Boardman, R., Smith, J. (2010) "Nuclear Hybrid Energy Systems: Imperatives, Prospects, and Challenges," *Energy Procedia*, 7, 51-54.
2. Bragg-Sitton, S.M., Boardman, R., Rabiti, C., O'Brien, J. (2020) "Reimagining future energy systems: Overview of the US program to maximize energy utilization via integrated nuclear-renewable energy systems," *Int J Energy Res*, 44 (10). https://doi.org/10.1002/er.5207.
3. Uchanin, V., Editor Steam Generator Systems: Operational Reliability and Efficiency. Chapter 17, Bonavigo, L. and De Salve, M., "Issues for Nuclear Power Plants Steam Generators," IntechOpen Ltd., London, United Kingdom (March 2011). DOI: 10.5772/14853
4. Buchheit, K.L., Smith, J.D., Guntupalli, Chen, C. (2016) "Techno-Economic Analysis of a Sustainable Coal, Wind, and Nuclear Hybrid Energy System," *Energy Fuels*, 30 (12) 10721–10729. https://doi.org/10.1021/acs.energyfuels.6b02113.
5. PFBC Environmental Energy Technology, Inc. PFBC: Competitive Clean Coal Power Utilizing Pressurized Fluidized Bed Combined-Cycle Technology http://www.pfbceet.com/literature/compressed_brochure.pdf.
6. Buchheit, K.L. "Process Design, Dynamics, and Techno-Economic Analysis of a Sustainable Coal, Wind, and Small Modular Nuclear Reactor Hybrid Energy System," *Doctoral Dissertation*, Department of Chemical and Biochemical Engineering, Missouri University of Science and Technology, Rolla, Missouri (2015).