Energy and exergy analyses of a hybrid small modular reactor and wind turbine system for trigeneration

Farrukh Khalid | Yusuf Bicer

Division of Sustainable Development (DSD), Hamad Bin Khalifa University (HBKU), Qatar Foundation (QF), Doha, Qatar

Correspondence
Farrukh Khalid, Division of Sustainable Development (DSD), Hamad Bin Khalifa University (HBKU), Qatar Foundation (QF), Doha, Qatar.
Email: fkhalid@hbku.edu.qa

Abstract
In this study, authors present a new hybrid nuclear small modular reactor system assisted with wind energy for net zero emissions trigeneration system. Small modular reactors bring multiple advantages including (a) improved thermal efficiency, (b) better building efficiency due to modularity, and (c) less operation and maintenance costs compared to standard nuclear power generation. Furthermore, the greenhouse gas emissions from small modular reactors are lower than regular counterparts. This study hybridizes small modular reactors with wind turbines for producing three useful commodities, namely electricity, hydrogen, and hot water. A two-step high-temperature thermochemical cycle (based on hydrogen chloride gas) is used for hydrogen production, and its performance in terms of energy and exergy efficiencies is evaluated. Additionally, the exergy and energy analyses (by writing balance equations for each component of the system) are carried out to determine the thermodynamic feasibility of the proposed system. In order to observe the effects of various parameters such as the temperature of the thermochemical cycle steps, inlet gas turbine temperature, the pressure ratio of the gas turbine, actual wind speed, and current density on the system performance, a detailed parametric study is conducted. The results of this study show that the overall system can achieve an energy efficiency of about 57.5% and exergy efficiency of about 38.1%.

KEYWORDS
exergy, high-temperature electrolysis, nuclear, thermochemical cycle, trigeneration, wind energy

1 | INTRODUCTION

At present, in most of the advanced countries, nuclear energy is a reliable and environmentally friendly source of energy. For instance, as of mid-July 2018, worldwide there were 31 countries where 413 nuclear reactors are being operational and produced 2500 TWh of electricity for the year 2017 (almost 10.3% of worlds’ electricity production) with an increase of 1% over the year 2016. Over the last 5 years, this share of electricity generation by nuclear in worlds’ electricity production is almost stable. Despite stable operation and environmentally friendly nature, there is a decline in the new nuclear plant constructions. The small modular reactors are designed to solve the issues like size and cost and can be suitable for both on- and off-site locations such as oil sand fields and mine sites.1,2 On the other hand, countries such as Canada have shown great interest in these SMRs as they have prepared a road map for the use of SMRs for the generation of electricity and other processes such as hydrogen production and industrial
heating. The Canadian SMR road map has the following major findings:

- For successful deployment of SMRs, the fleet approach is required.
- In Canada, the demonstration of SMR technology is essential.
- For deployment of SMRs in Canada, risk should be suitably shared among the different entities like governments, industries, and power generation companies.
- Hybridization of SMRs with renewable energy systems is greatly encouraged.

1.1 Literature review

SMRs are in fact one of the promising options for distributed power generation because their production capacities (generally <300 MW) are lower than nuclear power plants. In this way, they can be installed in remote locations, which will reduce electricity transmission loses. In addition, nuclear reactors are preferred to be integrated into many other energy systems such as desalination. Mitenkov and Polunichev considered a marine integrated small nuclear reactor for water desalination as well as power and heat production. Misra mentioned the fundamental challenges in the application of seawater desalination using nuclear power. They implied that the public perception of nuclear desalination is an important issue to be considered. Misra and Kupitz emphasized the importance of nuclear energy for desalination purposes. Kupitz and Crijns prepared a perspective paper about 25 years ago for using nuclear energy for seawater desalination. Khan et al. mentioned in their study that the option of small modular reactors (SMRs) is a good candidate for desalination technology.

SMRs are considered as one of the solutions for mitigating climate change as explained by Carless et al. and Iyer et al. Iyer et al. used an integrated model assessment for evaluating SMRs for climate change policies by selected scenarios based on the availability of large reactors. They compare market share of SMRs whether there will be large reactors or not. The unavailability of large reactors was limited due to the fact that new investment in large reactors cannot take place because of the barriers to nuclear deployment.

Carless et al. resulted in their life cycle assessment that SMRs can lower the GHG emissions almost 33%, from 13.6 g CO₂ eq/kWh in Standardized Nuclear Unit Power Plant Systems to 9.1 g CO₂ eq/kWh in SMRs. This is mainly attributed to the following advantages of SMRs:

- The decrease in assembly time and mass production
- Improved thermal efficiency
- Better assembly efficiency due to modularity
- Extended refueling rounds

- Easier decommissioning
- Inferior operation and maintenance expenses

The lower operating and maintenance costs of SMR were also mentioned by Liman. The results in that study showed that incremental construction and gradual shutdown steps can improve the economics of the small modular reactors by dealing with uncertainties of future prices. Alonso et al. compared the cost of electricity generation by SMRs, coal-fired power plants, and combined cycle power plants. They found that when coal prices are in the range of 80-120 US$/ton of coal, SMRs become competitive if a 30 US$/ton of CO₂ carbon tax is included for a 10% discount rate. In addition, for lower discount rates, SMRs can become more economical even though SMRs overnight capital cost is 5350 US$/kW. Compared to combined cycle power plants, for a 10% discount rate, SMRs are competitive when natural gas costs are above 9.48 US$/GJ (10 US$/MMBtu) and a 30 US$/ton of CO₂ carbon tax is included. Another cost reduction in SMRs is during decommissioning. Locatelli and Mancini investigated the cost breakdown of an SMR decommissioning project comparatively for SMR and large reactors. Their results showed that the decommissioning costs of an SMR with respect to a large reactor can decrease from three times higher to two times for the same capacity. Hong and Brook discussed the economic feasibility of SMRs for islands in Tasmania, Jeju, and Tenerife. They have concluded that SMRs is one of the carbon-neutral options and can be economically viable for the islands where land is limited and energy demand is high.

Integrating nuclear energy with renewable energy resources has also been investigated in the literature. Suman recently reviewed hybrid nuclear-renewable energy systems resulting in that integrating nuclear energy and renewable energy into a single hybrid energy system could manage to overcome the deficiencies available when they operate individually. Kim et al. analyzed a high-temperature steam electrolysis plant integrated into a light water reactor in nuclear-renewable hybrid energy systems. They have emphasized that hydrogen is a suitable storage medium and high-temperature steam electrolysis plant can act as a flexible load resource within the hybrid energy system. Jenkins et al. recently found out that flexible nuclear operation can lower power system operating costs, increases reactor owner revenues, and substantially reduces limitation of renewables. Locatelli et al. have discussed the use of SMRs for cogeneration purposes, that is, hydrogen and electricity. They have considered various options of hydrogen production, namely sulfur iodine-based thermochemical cycle, high-temperature steam electrolysis, and alkaline water electrolysis. They have concluded that high-temperature steam electrolysis with SMRs requires more research and development.

SMRs are also good candidates for integrating into supercritical CO₂ Brayton compression cycles. Park et al.
thermodynamically analyzed a supercritical carbon dioxide Brayton cycle (300-MWth) with small modular reactors (SMRs). They implied that the developed model can also be applied to other energy sources such as solar energy, bottoming cycle, and waste heat recovery system. SMR systems are even considered for underwater energy generation in the future. Bae et al.23 investigated the potential of very small modular type high temperature gas reactor (HTGR) with special attention given to the power conversion system. They compared the supercritical CO₂ cycle method with the helium Brayton cycle. In addition, Ahn and Lee24 evaluated and compared several closed Brayton cycles including supercritical CO₂ cycle, helium cycle, and nitrogen cycle in terms of cycle efficiency, component performance, and physical size. Shirvan et al.25 evaluated various reactor options in terms of safety, cost, and suitability for offshore underwater power generation. They considered five different designs (a) lead-bismuth fast reactor, (b) a novel organic cooled reactor, (c) an innovative superheated water reactor, (d) a boiling water reactor, and (e) an integral PWR featuring compact steam generators. These studies clearly indicate that SMRs are a suitable option for future energy generation, especially when coupled with other energy sources. Yang et al.26 presented the modeling and simulation of SMRs with CO₂ as the working fluid. They have considered supercritical CO₂ Brayton cycle for power conversion, and mass and energy balances for mathematical modeling using software called Modelica. Furthermore, they have also considered both air-cooled and water-cooled conditions and found that both cooling systems can achieve desired thermal efficiency. Kim et al.27 presented a conceptual design of an SMR coupled with supercritical CO₂ cycle for power generation using a passive decay heat removal system. For heat rejection, they have considered finned tube type air-cooled heat exchangers while shell and tube type heat exchangers were used for decay heat removal system.

According to the World Nuclear Industry Status Report, 2018,1 in the year 2017, the electricity generated by wind energy is about 1100 TWh. In India, 52.6 TWh of electricity is generated by wind in 2017. The potential benefits of generating hydrogen using nuclear energy or wind energy via thermochemical cycles can be found elsewhere.28–31

There are many studies reported on the use of nuclear energy for various applications ranging from electricity generation to pure water production. For instance, Kim and No32 stated the use of nuclear energy for sea water desalination via a high-temperature gas cooled reactor. Al-Zareer et al.33 have studied an integrated system based on nuclear energy for electricity and hydrogen production. They have employed a Cu-Cl cycle (a thermochemical cycle) for hydrogen production and coupled it to supercritical water reactor (SCWR). Boldon et al.34 reported the thermodynamic analysis of a small modular reactor assisted with wind energy. Their system is capable of producing electricity and hydrogen. They have utilized high-temperature water electrolysis for hydrogen production.

1.2 | Research gaps and objectives

Integration of renewable energy systems into a single hybrid energy system can eliminate the individual deficiencies of nuclear and renewable resources (such as intermittency). It will allow more flexible nuclear power plants for meeting the base load as well as peak loads. There is still a challenge associated with the wind energy, that is, of intermittent nature (unexpected wind speed variations). With the use of SMRs integrated into wind turbines for power generation, a more stable operation can be achieved. Hence, better demand-supply management is possible using hybrid SMR and wind energy systems. This will help energy trading and peak shaving/shifting in the future energy market. In addition, the SMRs can be used for nonelectrical applications such as hydrogen production and industrial heating. Thermochemical cycles such as sulfur iodine, hydrogen chloride (HCl), and copper chlorine can be coupled with nuclear plants assisted by wind energy for large-scale hydrogen production. There is a need to investigate the feasibility of these hybrid systems from a thermodynamic point of view to obtain the actual performance, which can prove the advantages of hybridization. There is very limited research on gas phase high-temperature HCl electrolysis in the literature. This new approach is utilized here for producing hydrogen in a thermochemical cycle. In this proposed system, the issue of energy storage is resolved by producing hydrogen. Hydrogen acts as an energy storage medium, which can then be utilized for peak demands through fuel cells, power generators etc.

The present study is unique in terms of hybridizing the small modular reactors and wind turbines for a net zero emission trigeneration system. Trigeneration is defined as producing three useful outputs, namely hydrogen, electricity, and hot water in this study. Furthermore, this study considers a two-step high-temperature thermochemical cycle for hydrogen production, where the working fluid is HCl in the gas phase. Hydrogen is a promising energy storage medium in the future energy portfolio. Feasibility of integrating a renewable energy source into small modular reactors has not been studied much in the literature. Therefore, based on this literature review and observed research gap, the following specific objectives are set for this study:

- To design a trigeneration system (hydrogen, electricity, hot water) running on power supplied by small modular reactors (SMRs) assisted with wind energy.
- To produce large-scale hydrogen using a two-step high-temperature thermochemical cycle (gas phase HCl)
and it is coupling with SMRs (showing the actual circuit of heat supplied to the thermochemical cycle) and wind energy.

- To assess the system performance thermodynamically in terms of exergy and energy efficiencies by performing a comprehensive thermodynamic study.
- To observe the effects of different operating parameters on the system performance.

2 | SYSTEM DESCRIPTION

A trigeneration system producing electricity, hot water, and hydrogen using nuclear energy assisted with wind energy is presented, and its schematic is depicted in Figure 1. The trigeneration system comprises of a nuclear reactor, a set of wind turbines, steam, and gas turbines, helium compressor, two water pumps, electrolyzer, a reverse Deacon reactor, splitter, mixer, and five heat exchangers (HEXs). The hot and compressed helium coming from the nuclear reactor core (state 1) is being used to provide the required heat to the reverse Deacon reactor. Helium after passing the reverse Deacon reactor (state 2) went through the HEX 1 where it is used to heat the steam to the reverse Deacon reactor temperature. After passing through the HEX 1, helium (state 3) is expanded in the gas turbine to produce the electric power. The expanded helium (state 4) is further used in HEX 2 where it loses the energy and used to heat the helium (state 9) that goes

![Schematic diagram of the nuclear system assisted with wind turbines for trigeneration](image-url)
inside the nuclear reactor. Before helium being compressed, it is further cooled down in HEX 3 (state 7). The compressed helium (state 8) is further heated in HEX 2. The hot hydrogen chloride gas coming out of reverse Deacon reactor (state 17) is get electrolyzed in electrolyzer with the help of electricity generated by the wind turbines to produce hydrogen ($H_2$) and chlorine ($Cl_2$) gases. The produced chlorine gas ($Cl_2$) is used in reverse Deacon reactor, thus making the closed thermochemical cycle for hydrogen ($H_2$) production. The heat loss from the electrolyzer is captured by the pressurized water (state 12) to produce pressurized steam (state 19) which then get expanded in the steam turbine to provide electricity. The expanded steam (state 21) is condensed in HEX 5; the condensed water coming out from the HEX 5 (state 22) is pumped to atmospheric pressure and then gets cooled to atmospheric temperature. Cooled water (state 27) enters the mixer where it gets mixed with another fresh stream of atmospheric water (state 27). The mixed water leaves the mixer as one stream (state 24) which is then pumped using Pump 2 to higher pressure (state 10). The pressurized water (state 10) enters into the HEX 3 and gets heated (state 11). The pressurized hot water (state 11) gets split into two steams (state 11 and state 12) with the help of a splitter. One stream (state 13) is used to heat the atmospheric water (state 6) to steam (state 14). After heating the atmospheric water, the pressurized water is used as one of the useful products from the proposed system (state 26). Thus, the whole integrated system works in harmony to produce three useful outputs, namely electricity, hot water, and hydrogen ($H_2$), using nuclear and wind energy sources.

3 | THERMODYNAMIC ASSESSMENT

To identify the thermodynamic behavior of the proposed system with different input conditions, exergy assessment is performed in addition to conventional (energy) assessment. In order to perform thermodynamic analysis of this trigen- eration system, there is a need to make conceptually correct assumptions. The following assumptions are invoked in this study:

- The system is in steady state.
- Heat exchangers and pipelines’ pressure drops are neglected.
- Zero heat loss is considered in heat exchangers.
- Chemical reactions proceed to completion.
- Wind-to-electric power conversion efficiency is considered 50%.
- The capacity factor of SMR is taken as 95%.

Most of the thermodynamic systems operate in steady-state conditions. It is quite common to neglect the pressure drops within the piping in these systems as well as heat losses in the heat exchangers. The maximum theoretical limit (Betz limit) is about 59.3% for wind turbines. Here, it is assumed about 50% energy conversion efficiency in the wind turbines for facilitating the wind-related calculations.

### 3.1 | Energy assessment

To perceive the performance of the system and two-step thermochemical cycle, energy efficiencies are utilized based on the first law of thermodynamics defined as follows:

#### 3.1.1 | Two-step thermochemical cycle

\[
\eta_{\text{en,cycle}} = \frac{m_{H_2} LHV_{H_2}}{W_{\text{elec}} + Q_{\text{reaction}} + Q_{\text{required}} - Q_{\text{loss,elec}}} \tag{1}
\]

where $W_{\text{elec}}$ is the work rate required by the electrolyzer, and $Q_{\text{reaction}}$ and $Q_{\text{required}}$ are the heat rates required in the reversed Deacon reaction, and water to steam conversion, respectively. Since in the proposed system electrolyzer losses ($Q_{\text{loss,elec}}$) are captured by the pressurized water, they are excluded from the energy definition. The details of computing the electrolyzer work rate ($W_{\text{elec}}$) are presented by Khalid et al.\(^{35}\)

#### 3.1.2 | Overall system

\[
\eta_{\text{en,ov}} = \frac{m_{H_2} LHV_{H_2} + W_{\text{net,elec}} + m_{26} h_{26} - m_{25} h_{25}}{W_{\text{wind,in}} + Q_{\text{core}}} \tag{2}
\]

where

\[
W_{\text{wind,in}} = \frac{1}{2} m_{\text{air}} V^2 \tag{3}
\]

The mass flow rate of air computed as

\[
m_{\text{air}} = \rho_{\text{air}} A V \tag{4}
\]

where $\rho_{\text{air}}$ is the density of air. The area swept by the wind turbine is evaluated as

\[
A = \pi \frac{D^2}{4} \tag{5}
\]

In the above definition, the net electric power ($W_{\text{net,elec}}$) is computed by the correlations used in the study conducted by Khalid et al.\(^{36}\)

The energy and exergy balance equations for the main components of the systems are tabulated in Table 1.

### 3.2 | Exergy assessment

For a detailed understanding of the system based on the second law of thermodynamics, exergy assessment is used. Similar to the previously defined energy efficiencies, the
TABLE 1 Energy and exergy balance equations for the main components of the systems

| Name of the component | Energy balance equations | Exergy balance equations |
|-----------------------|--------------------------|--------------------------|
| Nuclear Reactor       | m_1 h_1 + Q_{core} = m_1 h_1 | m_1 e_{x1} + E_{x,core} = m_1 e_{x1} + E_{x,core} |
| Gas turbine           | m_1 h_1 = m_1 h_1 + W_{p} | m_1 e_{x1} = W_{p} + m_4 e_{x4} + E_{x,gt} |
| Deacon Reactor       | m_1 h_1 + m_1 h_1 + m_1 h_1 + m_1 h_1 = m_1 h_1 + m_1 h_1 | m_1 e_{x1} + m_1 e_{x1} + m_1 e_{x1} + m_1 e_{x1} = m_1 e_{x1} + m_1 e_{x1} + m_2 e_{x2} + E_{x,DRD} |
| Compressor           | m_1 h_1 + W = m_1 h_1 | m_1 e_{x1} = W_{e} = m_1 e_{x1} + E_{x,gt} |
| Heat exchanger 1     | m_1 h_1 + m_1 h_1 = m_1 h_1 + m_1 h_1 | m_1 e_{x1} + m_1 e_{x1} = m_1 e_{x1} + m_1 e_{x1} + E_{x,HEX1} |
| Heat exchanger 2     | m_1 h_1 + m_1 h_1 = m_1 h_1 + m_1 h_1 | m_1 e_{x1} + m_1 e_{x1} = m_1 e_{x1} + m_1 e_{x1} + E_{x,HEX2} |
| Steam turbine        | m_1 h_{19} = W_{s} + m_1 h_1 | m_1 e_{x19} = W_{s} + m_1 e_{x19} + E_{x,gt} |
| Heat exchanger 3     | m_1 h_{10} + m_1 h_3 = m_1 h_{11} + m_1 h_3 | m_1 e_{x10} + m_1 e_{x3} = m_1 e_{x11} + m_1 e_{x3} + E_{x,HEX3} |
| Electrolyzer         | m_1 h_{16} + m_1 h_{12} + W_{elec} = m_25 h_{25} + m_1 h_{16} + m_1 h_{12} | m_1 e_{x16} + m_1 e_{x12} + W_{d,elec} = m_25 e_{x25} + m_1 e_{x16} + m_1 e_{x12} + E_{x,elec} |

exergy efficiencies of the two-step thermochemical cycle, and the overall system, respectively, are written as follows:

\[
\eta_{ex,cycle} = \frac{\dot{m}_{H_2} e_{xH_2}}{W_{elec} + \dot{E}_{x,\text{reaction}}\text{Q} - \dot{E}_{x,\text{loss,electrolyzer}}} \tag{6}
\]

\[
\eta_{ex,ov} = \frac{\dot{m}_{H_2} e_{xH_2} + \dot{W}_{\text{net,electric}} + \dot{m}_{25} e_{x25} - \dot{m}_{25} e_{x25}}{\dot{W}_{\text{wind,lin}} + \dot{E}_{x,core}} \tag{7}
\]

Since nuclear fission is a very high-temperature phenomenon, exergy rate associated with is equal to its energy rate. Thus, in this paper, we use \(\dot{E}_{x,core} = Q_{core}\) in the exergy efficiency as the reactor exergy input based on the literature.

4 | RESULTS AND DISCUSSION

To facilitate with the thermodynamic assessment, the state points with their thermodynamic properties such as temperature, pressure, specific enthalpy, and specific exergy are determined using software called Engineering Equation Solver (EES). These thermodynamic values with their state points are presented in Table 2. The present system can produce 0.78 kg/s of hydrogen with a thermochemical cycle having energy and exergy efficiencies of 43.5% and 39.2% (see Table 3). One can obtain around 290 MW of electricity from the system presented in this study with a value of 57.5% overall energy efficiency. It is to be also noted from the figure that the energy efficiency of the single generation process is less compared to the trigeneration process. However, cogeneration process energy and exergy efficiencies both are less compared to single generation process and this is due to the production of hydrogen. However, hydrogen production is considered as an asset which can be utilized during peak demand or can be transported to other parts.

To pinpoint the real exergy losses in the overall system, exergy destruction rates of key components are found (see Figure 2). The analysis reveals that the reactor core has the exergy destruction rate of around 198 MW, which is the largest among all the components of the system. 95 MW of exergy destruction rate occurs in the electrolyzer making it a significant contributor to the losses. Electrolyzer exergy destruction rates can be decreased with the improvement/advancement in the solid oxide membrane conductivity as the main losses from the electrolyzer are due to membrane losses (ie, Ohmic losses). The compressor exergy destruction rate is also noteworthy (44 MW).

4.1 | Effects of the outlet temperature of the nuclear reactor

The outlet temperature has an impact on the performance of the system which is illustrated in Figure 3. It is important to note that thermodynamic efficiencies (exergy and energy) of the overall system decrease with the increase in temperature. The electric power produced by the system, electrolyzer work rate, and rate of heat required for Deacon reaction increase with the rise in temperature. The increase in outlet temperature leads to more hydrogen production rate as more outlet temperature gives rise to more heat input to the reverse Deacon reaction (see Figure 4). From Figure 4, one can also observe that there is no change in the two-step cycle efficiencies. The thermodynamic efficiencies of the system reduce with the production of more hydrogen. Despite this, one should also produce hydrogen because it can be used as a storage medium for the excess electricity (when there is no peak demand) and can be proved as a worthy asset.

4.2 | Effect of the outlet temperature of the reverse Deacon reactor

The variation of thermodynamic efficiencies of the thermochemical cycle and hydrogen production rate with the outlet temperature of the reverse Deacon reactor is plotted in
Figure 5. As the temperature becomes to rise, the amount of produced hydrogen decreases without affecting the performance of the thermochemical cycle. This can be attributed to the fact that with a decrease in the amount of hydrogen produced, the electric power required by the electrolyzer is also reduced resulting in no variation in thermodynamic efficiencies of the thermochemical cycle.

The amount of heat supplied to the reverse Deacon reactor, electric power produced by the system and electrolyzer work rate all decrease with the increase in outlet temperature of the reverse Deacon reactor (see Figure 6). Although the energy and exergy efficiencies of the overall system increase, this trend is observed because if there is less heat supplied to the reverse Deacon reactor, less amount of hydrogen is produced resulting in lesser electric power consumption, eventually increasing the energy and exergy efficiencies of the overall system. There is a slight increase observed in the electric power produced by the gas turbine with the rise in outlet temperature of the reverse Deacon reactor. One should note from the Figure 1 that helium coming out of the reverse Deacon reactor affects the gas turbine inlet temperature, or in other words, the outlet temperature of the reverse Deacon reactor controls the inlet gas turbine temperature and is a well-established phenomenon that for the gas turbine, the electric output increases with the increase in inlet gas turbine temperature. Thus, a similar trend is also experienced here. The net electric power produced by the system decreases despite the increase in net electric work rate produced by the gas turbine cycle. This can be somewhat explained by the fact with the increase in temperature of the reverse Deacon reactor, the amount of hydrogen produced is less, which results in fewer electrolyzer losses eventually leading to less electric power produced by the steam turbine. Because there would be less amount of water required to capture the losses emitted by the electrolyzer. Hence, the total work rate produced by the system decreases.

| State No. | Fluid Type | T (°C) | P (kPa) | m (kg/s) | h (kJ/kg) | ex (kJ/kg) |
|-----------|------------|--------|---------|----------|-----------|------------|
| 1         | Helium     | 850.0  | 7000    | 439      | 5858      | 4872       |
| 2         | Helium     | 840    | 7000    | 439      | 5806      | 4834       |
| 3         | Helium     | 836.7  | 7000    | 439      | 5789      | 4822       |
| 4         | Helium     | 395.4  | 1750    | 439      | 3482      | 2442       |
| 5         | Helium     | 344.9  | 1750    | 439      | 3220      | 2302       |
| 6         | Water      | 25     | 101.3   | 0.779    | −15866    | 0          |
| 7         | Helium     | 30     | 1750    | 439      | 1585      | 1769       |
| 8         | Helium     | 334.9  | 7000    | 439      | 3185      | 3148       |
| 9         | Helium     | 385.3  | 7000    | 439      | 3447      | 3287       |
| 10        | Water      | 25.9   | 15199   | 808      | 122.7     | 15.1       |
| 11        | Water      | 120    | 15199   | 808      | 514.4     | 67.58      |
| 12        | Water      | 120    | 15199   | 32.5     | 514.4     | 67.58      |
| 13        | Water      | 120    | 15199   | 775.5    | 514.4     | 67.58      |
| 14         | Water      | 100   | 101.3   | 6.97     | −13282    | 542        |
| 15         | Water      | 630   | 101.3   | 6.97     | −12198    | 1094       |
| 16         | Hydrogen   | 630   | 101.3   | 28.21    | −2038     | 2551       |
| 17         | Chlorine   | 630   | 101.3   | 27.43    | 309.4     | 1885       |
| 18         | Oxygen     | 630   | 101.3   | 6.19     | 604.6     | 403.6      |
| 19         | Water      | 550   | 15199   | 32.5     | 3448      | 1511       |
| 20         | Hydrogen   | 630   | 101.3   | 0.779    | 8812      | 60562      |
| 21         | Water      | 45.8  | 10      | 32.5     | 2271      | 139.4      |
| 22         | Water      | 45.8  | 10      | 32.5     | 191.8     | 2.85       |
| 23         | Water      | 45.8  | 101.3   | 32.5     | 191.9     | 2.94       |
| 24         | Water      | 25    | 101.3   | 808      | 104.9     | 0          |
| 25         | Water      | 25    | 101.3   | 775.5    | 104.9     | 0          |
| 26         | Water      | 114.5 | 15199   | 775.5    | 491.2     | 62.08      |
| 27         | Water      | 25    | 101.3   | 32.5     | 104.9     | 0          |

*Calculated using NASA properties in EES.*

**TABLE 2** Thermodynamic data for trigeneration system
4.3 Effect of the operating temperature of the thermochemical cycle

Performance indicators of the system, thermochemical cycles, and various work and heat rates variations with the operating temperature of the thermochemical cycle are plotted in Figure 7. The rise in temperature leads to the decreases in net electric work produced by the system, amount of electric power required by the electrolyzer, and energy efficiency of the thermochemical cycle while the exergy efficiencies of the overall system, and thermochemical cycle increases. This is attributed to the fact that with an increase in operating temperature of the cycle, the electrolyzer losses (mainly membrane losses) decrease because much better proton conducting at elevated temperature results in a decrease in electrolyzer work rate with better exergy efficiencies of the overall system and cycle. The net work rate produced by the system decreases and can be explained by the fact that with a higher temperature of the cycle, losses would be less in the electrolyzer giving rise to less electric power produced by the steam turbine.
**Figure 4** Energy and exergy efficiencies of the thermochemical cycle, and the mass flow rate of hydrogen variation with the outlet temperature of the nuclear reactor.

**Figure 5** The effects of the outlet temperature of reverse Deacon reactor ($T_2$) on energy and exergy efficiencies of the thermochemical cycle, and mass flow rate of hydrogen.

**Figure 6** The effects of the outlet temperature of reverse Deacon reactor ($T_2$) on energy and exergy efficiencies, various work rates, and rate of heat reaction.
as Rankine cycle is driven by the heat losses from the electrolyzer (see Figure 1). The energy efficiency trend of the thermochemical cycle can be described by the fact that as the temperature increases, the heat losses from the electrolyzer decrease resulting in more heat input to the system (see Equation 1).

Variations of the total potential required by electrolyzer and gas turbine inlet temperature with the operating temperature of the cycle are shown in Figure 8. The gas turbine inlet temperature and electrolyzer potential both decrease with the elevation in operating temperature of the cycle.

4.4 Effects of the current density

Variations of all defined thermodynamic efficiencies in this study with the current density of the electrolyzer are plotted in Figure 9. All the efficiencies except for the energy efficiency of the cycle decrease with the increase in current density. There is no variation observed in the thermochemical cycle energy efficiency, and this trend is somewhat explained by the fact that the electrolyzer work rate increases with the current density and thus the losses from the electrolyzer. From Equation 1, one can see that in the expression of energy efficiency, heat loss from the electrolyzer is subtracted from the total energy input to the electrolyzer, while the total electric work required by electrolyzer includes the losses in form of ohmic losses (work rate losses). Thus, energy efficiency does not distinguish between heat and work losses, so there is a need of exergy efficiency definition so that the true determinations can be done. Hence, the exergy efficiency of the cycle is defined (see Equation 3). It clearly reflects those changes (heat and work rate losses) by the variation in exergy efficiency of the cycle (see Figure 9). This shows the clear benefit of exergy analysis over conventional energy analysis.
As the electrolyzer current density rises, the work rates and electrolyzer potential increase (see Figure 10). The increase in electrolyzer work rate and potential can be explained by the fact that with more current density, the ohmic losses would be much higher as current density directly related to ohmic losses by the Ohm’s law. The increase in net electric and Rankine cycle work rate can be explained by the fact that with more losses from the electrolyzer, the amount of steam required to capture these losses would be more. This results in more work rate produced by the Rankine cycle which eventually increases the overall net electric work rate.

4.5 Effects of pressure ratio

Pressure ratio changes on the various thermodynamic efficiencies defined in this study, work rates, and heat rate are shown in Figure 11. The more the pressure ratio, the less the exergy efficiency of the overall system while the more energy efficiency. The net electric work rate produced by the gas turbine cycle and overall system follows the same trend, that is, first rises then decreases. This can be explained by the fact that pressure ratio rises both the compressor and gas turbine works but after certain pressure ratio, there comes a situation in which the compressor work rate surpasses the gas turbine work rate resulting in the reduction in the net electric output by the gas turbine cycle which eventually leads to a decrease in the net electric work rate produced by the overall system. The trend of exergy and energy efficiencies of the overall system can be explained as with the rise in pressure ratio, the more amount of hot water is produced (see Figure 12) because as one can see from HEX 3, the more the temperature of the inlet stream (state 5), the more amount of cooling water is required to cool helium so
that it can enter compressor at atmospheric conditions (atmospheric conditions are favorable of the fact that compressor work rate increases with the increase in inlet compressor turbine temperature). One should also note from Figure 11 that as the pressure ratio rises, the rate of heat supplied/required by the nuclear reactor core also increases. Thus, the rise in pressure ratio results in the increase in energy efficiency while exergy efficiency declines. Because in energy efficiency, the output energy increases with more rate compared to the energy input making the overall energy efficiency of the system to rise. However, exergy efficiency distinguishes between quantity and quality of energy; thus, although the amount of hot water produced by the system increases, the exergy efficiency decreases. This is because the rate at which the system output (hot water) increase is less compared to the rate at which system input (rate of heat in reactor core) increases.

**FIGURE 11** Pressure ratio effects on the various thermodynamic efficiencies, work rates, and rate of heat reaction

**FIGURE 12** The effects of pressure ratio on the mass flow rate of hot water, and various exergy destruction rates

### 4.6 | Effect of wind velocity

The effects of variation in wind speed on the energy and exergy efficiencies of the overall system are plotted in Figure 13 for Lusail City, Qatar. The wind speed data used for this graph are obtained by elevating the measured wind speed data at 10 m to 120 m (the wind speed data in the figure are from June 2017 to May 2018). As the wind speed changes, both the efficiencies, namely exergy and energy, change. This can be explained by the fact as the wind speed increases, the work rate generated by wind turbine increases resulting in overall increase in efficiencies. From the figure, it is clearly visible that the net electric work rate generated by the overall system increases with the increase in wind speed. It is to be noted from the figure that the system exhibits the best exergy efficiency in the month of August as in this month the wind speed is maximum for the specific location.
5 | CONCLUSIONS

The conventional nuclear energy systems started with single generation in which there is only power output. Then, the waste heat has also been considered as an asset for further improvement; hence, the transition from single to cogeneration systems started to be considered. Nowadays, trigeneration systems are being considered for increasing the efficiencies by either combined systems, cascaded, or hybridized systems. Hence, it is important to consider, study, design, analyze, and implement trigeneration systems from a thermodynamic point of view to reveal their high potentials. Therefore, in this study, a detailed thermodynamic assessment of a trigeneration system that can produce hydrogen, electricity, and hot water is reported here. The proposed system utilizes small modular reactors as well as wind turbines in a hybrid manner. Small modular reactors are considered a promising power generation technique in the near future. The viability of the proposed system is assessed based on the first and second law of thermodynamics. The obtained results show that the overall system can run at 57.5% energetic efficiency and 38.1% exergetic efficiency. Furthermore, it is also found that the use of SMRs with wind for trigeneration purpose can achieve much higher energy efficiency compared to single generation process (energy efficiency, 47.5%) and much higher exergy efficiency compared to cogeneration (exergy efficiency, 34.8%). The reactor core and the electrolyzer are the main contributors of the exergy losses. With the employment of the presented thermochemical cycle, which utilizes wind and nuclear energy sources, a large amount of hydrogen production rate can be achieved as found in this study. Using SMRs combined with wind turbines, a more stable grid operation can be achieved with a better demand-supply management. The results of the current study will help the researchers/designers around the world to consider small modular reactors (SMRs) for integration with renewable energy sources such as wind and solar for multiple production of useful commodities.

ACKNOWLEDGMENTS

The authors acknowledge the support provided by the Hamad Bin Khalifa University, Qatar Foundation. The publication of this article was funded by the Qatar National Library.

Nomenclature

| Symbol | Definition |
|--------|------------|
| A      | Swept area (m²) |
| D      | Rotor diameter (m) |
| ex     | Specific exergy (kJ/kg) |
| Ex     | Exergy rate (MW) |
| h      | Specific enthalpy (kJ/kg) |
| m      | Mass flow rate (kg/s) |
| P      | Pressure (kPa) |
| Q      | Heat rate (MW) |
| T      | Temperature (°C) |
| V      | Velocity (m/s) |
| W      | Work rate (MW) |

Acronyms

| Acronym | Definition |
|---------|------------|
| EES     | Energy Equation Solver |
| HCl     | Hydrogen Chloride |
| HEX     | Heat Exchanger |
| HTGR    | High Temperature Gas Reactor |
| PWR     | Pressurized Water Reactor |
| SCWR    | Super Critical Water Reactor |
| SMRs    | Small Modular Reactors |
Greek Letters

\[ \begin{align*}
\rho & \text{ density} \\
\eta & \text{ efficiency}
\end{align*} \]

Subscripts

\[ \begin{align*}
c & \text{ compressor} \\
\text{elect} & \text{ electrolyzer} \\
\text{en} & \text{ energy} \\
\text{ex} & \text{ exergy} \\
gt & \text{ gas turbine} \\
\text{ov} & \text{ overall} \\
\text{RC} & \text{ Rankine cycle} \\
\text{RDR} & \text{ reverse Deacon reactor} \\
\text{st} & \text{ steam turbine} \\
1,2,\ldots & \text{ state numbers}
\end{align*} \]

ORCID

Farrukh Khalid https://orcid.org/0000-0003-4600-3496
Yusuf Bicer https://orcid.org/0000-0003-4753-7764

REFERENCES

1. Schneider M, Froggatt A. *The World Nuclear Industry Status Report 2018*. Paris: A Mycle Schneider Consulting Project; 2018.
2. Ikegawa T, Kawabata Y, Ishii Y, Matsuura M, Hirako S, Hoshi T. The plant feature and performance of double MS (Modular Simplified and Medium Small Reactor). *J Eng Gas Turbines Power*. 2010;132(1):015001.
3. Canadian Small Modular Reactor Deployment to Be Featured at International SMR Gathering - Canadian Nuclear Laboratories [Online]. http://www.cnl.ca/en/home/news-and-publications/news-releases/2018/canadian-small-modular-reactor-deployment. aspx. Accessed September 20, 2018.
4. Canada Mapping a Strategy for the Next Generation of Nuclear Reactor Technology - Canada.Ca [Online]. https://www.canada.ca/en/natural-resources-canada/news/2018/02/canada_mapping_a_strategy_for_the_next_generation_of_nuclear_reactor_tech.html. Accessed September 20, 2018.
5. Canadian Small Modular Reactor Roadmap Steering Committee. A Call to Action: A Canadian Roadmap for Small Modular Reactors. Ottawa, ON, Canada; 2018.
6. Khalid F, Dincer I, Rosen MA. Comparative assessment of CANDU 6 and sodium-cooled fast reactors for nuclear desalination. *Desalination*. 2016;379:182-192.
7. Mitenkov FM, Polunichev VI. Small nuclear heat and power cogeneration stations and water desalination complexes on the basis of marine reactor plants. *Nucl Eng Des*. 1997;173(1–3):183-191.
8. Misra BM. Seawater desalination using nuclear heat/electricity — prospects and challenges. *Desalination*. 2007;205(1–3):269-278.
9. Misra BM, Kupitz J. The role of nuclear desalination in meeting the potable water needs in water scarce areas in the next decades. *Desalination*. 2004;166:1-9.
10. Kupitz J, Crijns MJ. Perspectives of nuclear energy for seawater desalination. *Desalination*. 1994;99(2–3):329-344.
11. Khan SU-D, Khan SU-D, Danish SN, Orfi J, Rana UA, Haider S. Nuclear energy powered seawater desalination. In: Gude VG, ed. *Renewable Energy Powered Desalination Handbook*. Oxford, UK: Butterworth-Heinemann; 2018: 225-264.
12. Carless TS, Griffin WM, Fischbeck PS. The environmental competitiveness of small modular reactors: a life cycle study. *Energy*. 2016;114:84-99.
13. Iyer G, Hultman N, Fetter S, Kim SH. Implications of small modular reactors for climate change mitigation. *Energy Econ*. 2014;45:144-154.
14. Liman J. Small modular reactors: methodology of economic assessment focused on incremental construction and gradual shutdown options. *Prog Nucl Energy*. 2018;108:253-259.
15. Alonso G, Bilbao S, del Valle E. Economic competitiveness of small modular reactors versus coal and combined cycle plants. *Energy*. 2016;116:867-879.
16. Locatelli G, Mancini M. Competitiveness of small-medium, new generation reactors: a comparative study on decommissioning. *J Eng Gas Turbines Power*. 2010;132(10):102906.
17. Hong S, Brook BW. Economic feasibility of energy supply by small modular nuclear reactors on small islands: case studies of Jeju, Tasmania and Tenerife. *Energies*. 2018;11:2587.
18. Suman S. Hybrid nuclear-renewable energy systems: a review. *J Clean Prod*. 2018;181:166-177.
19. Kim JS, Boardman RD, Bragg-Sitton SM. Dynamic performance analysis of a high-temperature steam electrolysis plant integrated within nuclear-renewable hybrid energy systems. *Appl Energy*. 2018;228:2090-2110.
20. Jenkins JD, Zhou Z, Ponciroli R, et al. The benefits of nuclear flexibility in power system operations with renewable energy. *Appl Energy*. 2018;222:872-884.
21. Locatelli G, Boarin S, Fiordaliso A, Ricotti ME. Load following Small Modular Reactors (SMR) by cogeneration of hydrogen: a techno-economic analysis. *Energy*. 2018;148:494-505.
22. Park HJ, Park HS, Kwon JG, Kim TH, Kim MH. Optimization and thermodynamic analysis of supercritical CO2 Brayton re-compression cycle for various small modular reactors. *Energy*. 2018;160:520-535.
23. Bae SJ, Lee J, Ahn Y, Lee JI. Preliminary studies of compact Brayton cycle performance for small modular high temperature gas-cooled reactor system. *Ann Nucl Energy*. 2015;75:11-19.
24. Ahn Y, Lee JI. Study of various Brayton cycle designs for small modular sodium-cooled fast reactor. *Nucl Eng Des*. 2014;276:128-141.
25. Shirvan K, Ballinger R, Buongiorno J, Forsberg C, Kazimi M, Todreas N. Technology selection for offshore underwater small modular reactors. *Nucl. Eng. Technol*. 2016;48(6):1303-1314.
26. Yang Y, Guo Q, Lin J, et al. Modeling and Simulating Supercritical CO2 Brayton cycle in SMR using Modelica. 25th International Conference on Nuclear Engineering, ASME Proceedings, Innovative Nuclear Power Plant Design and New Technology Application; 2017: V003T13A009.
27. Kim SG, Yu H, Moon J, et al. A concept design of supercritical CO2 cooled SMR operating at isolated microgrid region. *Int J Energy Res*. 2017;41:512-525.
28. Khalid F, Dincer I, Rosen MA. Co-production of hydrogen and copper from copper waste using a thermochemical Cu–Cl cycle. *Energy Fuels*. 2018;32(2):2137-2144.
29. Lewis D. Hydrogen and its relationship with nuclear energy. *Prog Nucl Energy*. 2008;50(2–6):394-401.
30. Al-Zareer M, Dincer I, Rosen MA. Performance analysis of a supercritical water-cooled nuclear reactor integrated with a combined cycle, a Cu-Cl thermochemical cycle and a hydrogen compression system. Appl Energy. 2017;195:646-658.
31. Al-Zareer M, Dincer I, Rosen MA. Development and analysis of an integrated system with direct splitting of hydrogen sulfide for hydrogen production. Int J Hydrogen Energy. 2016;41:20036-20062.
32. Kim HS, No HC. Thermal coupling of HTGRs and MED desalination plants, and its performance and cost analysis for nuclear desalination. Desalination. 2012;303:17-22.
33. Al-Zareer M, Dincer I, Rosen MA. Development and assessment of a novel integrated nuclear plant for electricity and hydrogen production. Energy Convers. Manag. 2017;134:221-234.
34. Boldon L, Sabharwall P, Rabiti C, Bragg-Sitton SM, Liu L. Thermodynamic exergy analysis for small modular reactor in nuclear hybrid energy system. EPI Nucl. Sci. Technol. 2016;2:23.
35. Khalid F, Dincer I, Rosen MA. Model development and analysis of a novel high-temperature electrolyser for gas phase electrolysis of hydrogen chloride for hydrogen production. Int J Hydrogen Energy. 2018;43(19):9112-9118.
36. Khalid F, Dincer I, Rosen MA. Analysis and assessment of a gas turbine-modular helium reactor for nuclear desalination. J. Nucl. Eng. Radiat. Sci. 2016;2(3):31014.
37. Rosen MA. Energy- and exergy-based comparison of coal-fired and nuclear steam power plants. Exergy An Int J. 2001;1(3):180-192.
38. Klein SA. EES: Engineering Equation Solver – F-Chart Software: Engineering Software; 2018.

How to cite this article: Khalid F, Bicer Y. Energy and exergy analyses of a hybrid small modular reactor and wind turbine system for trigeneration. Energy Sci Eng. 2019;7:2336–2350. https://doi.org/10.1002/ese3.327