**High-Temperature Nuclear Cogeneration Utilizing Supercritical CO2 for Enhanced Thermal Efficiency**

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ABSTRACT

Clean energy production is a challenge, which was so far addressed mainly in the electric power sector. More energy is needed in the form of heat for both district heating and industry. Nuclear power is the only technology fulﬁlling all 3 sustainability dimensions, namely economy, security of supply and environment. In this context, the European Nuclear Cogeneration Industrial Initiative (NC2I) has launched the projects NC2I-R and GEMINI+ aiming to prepare the deployment of High Temperature Gas-cooled Reactors (HTGR) for this purpose.

Keywords: Nuclear; Supercritical ; Brayton cycle

1. **Introduction**

The global energy demand is steadily rising, while fossil fuel resources are being depleted, and the threat of climate change looms large. The combustion of fossil fuels generates greenhouse gases, which significantly harm the environment and are a primary driver of unpredictable global climate change [1]. To tackle these global energy and environmental challenges, it is essential to enhance the energy efficiency of our industries [2]. Thus, identifying alternative energy sources is essential to address this urgent global challenge. Researchers are exploring several viable options for energy generation, including solar energy [3], nuclear power [4], geothermal energy, flue gas from biogas combustion, and waste heat [5]. Utilizing clean energy, reducing pollutant emissions, and enhancing energy conversion efficiency are key strategies to combat the rising demand for fossil fuels and severe environmental pollution [6]. The supercritical carbon dioxide (s) is a promising solution, offering an eco-friendly, non-toxic, inexpensive, and inert working fluid [7]. This cycle achieves higher efficiency than conventional power cycles, particularly when used with medium- and high-temperature heat sources like waste heat, solar energy, and nuclear energy. Nuclear energy has seen rapid development recently due to its environmental friendliness, cost-effectiveness, and reliability. With the advancement of Generation IV nuclear reactors, the future of nuclear power generation looks promising [8].

Clean energy production is a top priority in Europe and is increasingly recognized as a global necessity. To date, most efforts have focused on electric power generation due to its relatively straightforward solutions. However, electricity represents only 18% of total energy consumption. Other sectors, such as heating and transportation, rely almost entirely on fossil fuels like natural gas, oil, and coal, which are major sources of high emissions [9]. In Europe, electricity constitutes 24% of energy consumption, while heating and cooling for residential and industrial purposes account for 50%. Nearly all of the heat derived in this sector comes from combustion. Therefore, an effective European energy policy must prioritize addressing this sector, even though it often goes unnoticed by the general public. The anticipated political and socio-economic benefits of such a policy are substantial [10]. The European Nuclear Cogeneration Industrial Initiative has conducted the GEMINI+ project with the aim of advancing the industrial demonstration of a High Temperature Gas-cooled Reactor (HTGR) power plant for cogeneration purposes [11].

The srecompression cycle presents a more efficient, significantly simpler, and more compact alternative to the superheated steam cycle. Compared to the helium Brayton cycle, it is notably less complex. At 550°C, the srecompression cycle achieves a thermal efficiency of 46%, matching the helium Brayton cycle's efficiency, which is only reached at 800°C [12]. To meet electrical power needs, an energy conversion system that matches its core power and temperature is crucial. Due to the high thermal efficiency and power output requirements, a dynamic power cycle system is preferred. With a core outlet temperature up to 700°C, the Rankine cycle is unsuitable because it lacks compactness and efficiency. Thus, the Brayton cycle system is chosen. The supercritical carbon dioxide (s) Brayton cycle is promising for its high thermal efficiency, compact design at turbine inlet temperatures of 500°C to 700°C, and reduced water consumption [13]. In the EU, 26% of industrial heat demand requires temperatures above 400°C, which is mainly met by burning fossil fuels [14]. In the UK, the iron and steel, mineral products, and food and drink sectors are the most energy-intensive, consuming over 50% of industrial process heat [15]. Industrial heat applications account for 14% of the UK's carbon dioxide emissions. High-temperature heat from nuclear power plants could potentially eliminate these emissions, but the use of nuclear energy for processing heat is still limited internationally [16]. Europe is currently facing major issues with material and energy resources that threaten industrial operations. Considering the advancements and benefits of small modular reactors (SMRs), [17]propose integrating SMRs into regions with industrial plants. The srecompression cycle is ideal for nuclear reactors with core outlet temperatures above 500°C, in both direct and indirect versions. Additionally, it has the potential to reduce capital costs compared to Rankine steam or helium Brayton cycles [18]. European Commission report[19] summarizes the energy consumption breakdown in the EU27 for 2005 and 2009, as shown in the Table 1. The data for the first four columns is sourced from EURSTAT, while the useful heat demand is estimated in his report. The estimated useful heat consumption for the industry was 5,349 PJ in 2005 and 4,434 PJ in 2009. Fig. 1, presents the projected useful heat demand in the industrial sector. High Temperature Gas-cooled Reactors (HTGR) can address much of this demand. Development programs in the UK, Germany, and the US, along with R&D projects in Europe, China, Japan, South Korea, and other countries, have advanced HTGR technology to a relatively high Technology Readiness Level [20]. Currently, the primary market for processing heat relies on steam at around 550°C. However, there is a significant and expanding demand for bulk hydrogen, which holds substantial potential for further growth. This paper focuses on GEMINI+ studies investigating the utilization of process heat from a nuclear cogeneration s cycle for various industrial applications, which are of interest to many industrialized countries.

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| **Table 1.** Break-down of energy consumption in European Industry. | | | | | | |
| PJ | Total Final energy | Total Final energy | Electrical energy | Electrical energy | Useful heat demand | Useful heat demand |
| Years | 2005 | 2009 | 2005 | 2009 | 2005 | 2009 |
| Iron and steel | 2622 | 1853 | 488 | 393 | 1695 | 1147 |
| Nonferrous metals | 486 | 373 | 291 | 223 | 149 | 113 |
| Chemicals | 2480 | 2109 | 736 | 629 | 955 | 877 |
| Nonmetallic minerals | 1820 | 1529 | 298 | 267 | 1209 | 937 |
| Paper and pulp | 1476 | 1383 | 510 | 443 | 549 | 512 |
| Food, drink and tobacco | 1261 | 1149 | 401 | 393 | 481 | 418 |
| Textiles | 331 | 216 | 119 | 85 | 120 | 72 |
| Other industries | 3163 | 2669 | 1228 | 1099 | 191 | 358 |
| Total | 13640 | 11282 | 4072 | 3532 | 5349 | 4434 |

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| A graph of different colored bars  Description automatically generated |
| **Fig. 1.** Estimated useful heat demand in the European Industry |

1. **sCO2 Brayton cycle**
   1. *sCO2 as working fluid*

Supercritical carbon dioxide (s) power cycles offer the potential for higher thermal efficiencies and lower capital costs compared to current steam-based power cycles. These distinctive attributes of s are generating significant interest in its application for power generation [21]. Carbon dioxide reaches its critical pressure (7.3773 MPa) and critical temperature (304.12 K) at the critical point. As illustrated in Fig. 2, shas a density similar to liquid but retains the viscosity and diffusion properties of a gas, exhibiting gas-like behavior with liquid density during expansion. It is non-toxic, non-corrosive, non-flammable, and non-explosive, with abundant availability and a reasonable price—costing just 1/10th of helium and 1/70th of the organic working fluid R-134a. Therefore, recycling is unnecessary. Additionally, it is compatible with standard materials and lubricants and poses no environmental harm.

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| Diagram of a diagram of liquid and gas  Description automatically generated |
| **Fig. 2.** Carbon dioxide pressure-temperature phase diagram |

Compared to other working fluids used in the supercritical Brayton cycle, carbon dioxide offers advantageous qualities such as a low critical point and high critical density. The physical properties of CO2 are detailed in Table 2.

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| **Table 2.** Properties of selected working fluids for the supercritical Brayton cycle. | | | | |
| **Fluids** |  |  |  |  |
| Molecular weight | 44.01 | 18.015 | 4.0026 | 28.965 |
| Critical density/kg.m−3 | 467.6 | 322 | 72.567 | 342.68 |
| Critical temperature/K | 304.13 | 647.1 | 5.1953 | 132.53 |
| Critical pressure/MPa | 7.3773 | 22.064 | 0.2276 | 3.786 |

1. **System Description and Assumption**

The schematic diagram in Figure 3 represents an advanced nuclear cogeneration system that integrates a supercritical carbon dioxide (sCO₂) Brayton cycle for power generation and a steam supply system for external use. Operating at a thermal power of 180 MWth, the nuclear reactor heats the working fluid to 750°C at a pressure of 6 MPa. The heated sCO₂ exits the reactor and enters a heat exchanger, where it transfers its thermal energy to a secondary loop. Once its heat is transferred, the working fluid cools to 325°C and is recirculated back to the reactor by a pump.

In the secondary loop, the process begins at the heat exchanger, where the sCO₂ heated by the primary loop is directed to a turbine. The high-temperature, high-pressure CO₂ expands through the turbine, generating mechanical work to drive a generator (G), which produces the electricity needed for the continuous operation of the nuclear cycle. The fluid exiting the turbine then flows into a recuperator, where it preheats the compressed working fluid before it returns to the heat exchanger. After the recuperator, the fluid is further cooled by a cooler and then compressed by the compressor (C). The compressed fluid is then pumped back to the heat exchanger, completing the cycle.

Moreover, the system incorporates a reboiler designed to provide superheated steam at 540°C and 13.8 MPa to an end-user site, delivering 64 kg/s (equivalent to 230 t/h or approximately 165 MWth of power). This integrated approach efficiently utilizes nuclear energy by combining the sCO₂ Brayton cycle for primary power generation with a reboiler for producing high-pressure steam. The recuperator in the sCO₂ Brayton cycle enhances thermal efficiency by preheating the compressed working fluid, while the heat recovery steam reboiler maximizes energy utilization by generating high-pressure steam for external use.

### Key Assumptions:

1. **Thermal Power and Temperature**: The nuclear reactor operates at a thermal power of 180 MWth, heating the sCO₂ to 750°C at a pressure of 6 MPa. The cooled sCO₂ returns to the reactor at 325°C.
2. **Secondary Loop Operations**: The sCO₂ in the secondary loop undergoes the following processes:
   * Expansion in the turbine to generate mechanical work and electricity.
   * Preheating in the recuperator using the exhaust from the turbine.
   * Further cooling in the cooler.
   * Compression in the compressor before returning to the heat exchanger.
3. **Reboiler**: The reboiler is designed to provide superheated steam at 540°C and 13.8 MPa to the end-user site, delivering 64 kg/s (approximately 165 MWth).
4. **Efficiency Enhancements**: The recuperator increases thermal efficiency by preheating the compressed working fluid before it enters the heat exchanger, while the reboiler ensures efficient energy utilization by generating high-pressure steam for external applications.
5. **Continuous Cycle**: The system operates in a continuous cycle, with sCO₂ being recirculated through the reactor, heat exchanger, turbine, recuperator, cooler, and compressor.

This comprehensive nuclear cogeneration system leverages the high thermal efficiency of the sCO₂ Brayton cycle and the effective use of waste heat through the reboiler to optimize energy production and utility.

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| **A diagram of a machine  Description automatically generated** |
| **Fig. 3.** Schematic layout of nuclear cogeneration with sCO2 Brayton cycle. |

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| A diagram of a cycle  Description automatically generated |
| **Fig. 4.** Temperature-entropy diagram cascading nuclear cogeneration with cycle. |

The T-S diagram represents the temperature-entropy relationship at various state points in the cycle. The state points are plotted, and the saturation dome is included to provide a visual representation of the phase boundaries. The diagram helps in understanding the thermodynamic behavior of the cycle and identifying the efficiency improvements.

1. **Thermodynamic Modelling**

The thermodynamic cycle modeled in this study consists of several components including a reactor, compressor, turbocirculator, reboiler, heater, economizer, and recuperator. The modeling involves calculating the enthalpy, temperature, and entropy at various state points within the cycle. The calculations use the CoolProp library to determine the thermodynamic properties of the working fluids (CO2 and He). Below is a detailed description of the mathematical modeling for each component in the cycle.

**1. Reactor**

The reactor provides thermal power to the cycle. The enthalpy change across the reactor is given by:

Equation 1

Where:

* ​ is the thermal power of the reactor.
* is the mass flow rate of the reactor.
* and are the inlet and outlet enthalpies of the reactor, respectively.

The mass flow rate of helium in the reactor is calculated using the given thermal power and the enthalpy change:

Equation 2

**2. Compressor**

The compressor increases the pressure of the working fluid (CO2). The isentropic efficiency of the compressor is used to determine the actual enthalpy at the outlet:

Equation 3

Where:

* is the outlet enthalpy.
* is the isentropic outlet enthalpy.
* is the compressor efficiency.

The isentropic outlet enthalpy () is determined using the inlet entropy () and the outlet pressure ():

Equation 4

The actual outlet temperature and entropy are then calculated using:

Equation 5

Equation 6

**3. Turbo-circulator**

The turbo-circulator operates similarly to the compressor but in the opposite direction, where it expands the working fluid:

Equation 7

Where:

* is the outlet enthalpy.
* is the isentropic outlet enthalpy.
* is the turbocirculator efficiency.

The isentropic outlet enthalpy ( is determined using the inlet entropy () and the outlet pressure ():

Equation 8

The actual outlet temperature and entropy are then calculated using:

Equation 9

Equation 10

#### **4. Reboiler**

The reboiler heats the working fluid by condensing steam. The thermal power supplied by the reboiler is:

Equation 11

Where:

* is the thermal power of the reboiler.
* is the mass flow rate of the reboiler.
* and are the inlet and outlet enthalpies of the reboiler.

#### **5. Heater**

The heater transfers thermal energy from the reactor to the working fluid. The enthalpy change across the heater is given by:

Equation 12

Where:

* is the thermal power of the heater.
* and are the inlet and outlet enthalpies of the heater.
* is the mass flow rate of CO2 in the heater.

The outlet temperature and entropy are then calculated using:

Equation 13

Equation 14

#### **6. Economizer**

The economizer preheats the working fluid using heat from the turbine exhaust. The enthalpy change across the economizer is given by:

Equation 15

Where:

* is the thermal power of the economizer.
* and are the inlet and outlet enthalpies of the economizer.
* is the mass flow rate of CO2 in the economizer.

The outlet temperature and entropy are then calculated using:

Equation 16

Equation 17

#### **7. Recuperator**

The recuperator improves cycle efficiency by recovering waste heat from the turbine exhaust and using it to preheat the working fluid before it enters the heater. The enthalpy change across the recuperator is given by:

Equation 18

Equation 19

Where:

* and are the outlet enthalpies on the hot and cold sides of the recuperator, respectively.
* and are the inlet enthalpies on the hot and cold sides of the recuperator, respectively.
* is the ideal outlet enthalpy.

The overall cycle efficiency and net power output are calculated as:

Equation 20

Equation 21

Where:

* is the Turbine work
* is the Compressor work

The thermodynamic properties at various state points in the cycle are calculated using the CoolProp library. The properties include enthalpy (h), temperature (T), and entropy (s). The library functions are used to compute these properties based on the state variables (pressure and temperature or enthalpy and pressure).

**Results and Discussion**

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| **A graph of a graph showing the effect of a turbine efficiency  Description automatically generated** | **A graph of a graph showing a green line  Description automatically generated with medium confidence** |
| **A rainbow colored lines  Description automatically generated with medium confidence** | **A rainbow colored chart of different colors  Description automatically generated with medium confidence** |
| **A rainbow colored chart of temperature  Description automatically generated with medium confidence** | **A rainbow colored lines with numbers  Description automatically generated with medium confidence** |
| **A rainbow colored bars of pressure  Description automatically generated with medium confidence** | **A rainbow colored lines with numbers  Description automatically generated with medium confidence** |

1. **Conclusion**

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**References**

[1] K. Calvin, D. Dasgupta, G. Krinner, A. Mukherji, P.W. Thorne, C. Trisos, J. Romero, P. Aldunce, K. Barrett, G. Blanco, W.W.L. Cheung, S. Connors, F. Denton, A. Diongue-Niang, D. Dodman, M. Garschagen, O. Geden, B. Hayward, C. Jones, F. Jotzo, T. Krug, R. Lasco, Y.-Y. Lee, V. Masson-Delmotte, M. Meinshausen, K. Mintenbeck, A. Mokssit, F.E.L. Otto, M. Pathak, A. Pirani, E. Poloczanska, H.-O. Pörtner, A. Revi, D.C. Roberts, J. Roy, A.C. Ruane, J. Skea, P.R. Shukla, R. Slade, A. Slangen, Y. Sokona, A.A. Sörensson, M. Tignor, D. van Vuuren, Y.-M. Wei, H. Winkler, P. Zhai, Z. Zommers, J.-C. Hourcade, F.X. Johnson, S. Pachauri, N.P. Simpson, C. Singh, A. Thomas, E. Totin, A. Alegría, K. Armour, B. Bednar-Friedl, K. Blok, G. Cissé, F. Dentener, S. Eriksen, E. Fischer, G. Garner, C. Guivarch, M. Haasnoot, G. Hansen, M. Hauser, E. Hawkins, T. Hermans, R. Kopp, N. Leprince-Ringuet, J. Lewis, D. Ley, C. Ludden, L. Niamir, Z. Nicholls, S. Some, S. Szopa, B. Trewin, K.-I. van der Wijst, G. Winter, M. Witting, A. Birt, M. Ha, IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland., 2023. https://doi.org/10.59327/IPCC/AR6-9789291691647.

[2] B. Khan, M.H. Kim, Energy and Exergy Analyses of a Novel Combined Heat and Power System Operated by a Recuperative Organic Rankine Cycle Integrated with a Water Heating System, Energies (Basel) 15 (2022). https://doi.org/10.3390/en15186658.

[3] G. Li, G. Du, G. Liu, J. Yan, Study on the dynamic characteristics, control strategies and load variation rates of the concentrated solar power plant, Appl Energy 357 (2024). https://doi.org/10.1016/j.apenergy.2023.122538.

[4] J. Syblík, J. Štěpánek, L. Veselý, S. Entler, V. Dostál, Preliminary design of supercritical CO2 axial compressor for fusion and nuclear power plants, Fusion Engineering and Design 192 (2023). https://doi.org/10.1016/j.fusengdes.2023.113770.

[5] M. Biondi, A. Giovannelli, G. Di Lorenzo, C. Salvini, Techno-economic analysis of a sCO2 power plant for waste heat recovery in steel industry, Energy Reports 6 (2020) 298–304. https://doi.org/10.1016/j.egyr.2020.11.147.

[6] N.A. Mohammed Almefreji, B. Khan, M.-H. Kim, machines Thermodynamic Performance Analysis of Solar Based Organic Rankine Cycle Coupled with Thermal Storage for a Semi-Arid Climate, (2021). https://doi.org/10.3390/machines.

[7] Q. Zhao, J. Xu, M. Hou, D. Chong, J. Wang, W. Chen, Dynamic characteristic analysis of SCO2 Brayton cycle under different turbine back pressure modes, Energy 293 (2024). https://doi.org/10.1016/j.energy.2024.130563.

[8] J. Tang, Q. Zhang, Z. Zhang, Q. Li, C. Wu, X. Wang, Development and performance assessment of a novel combined power system integrating a supercritical carbon dioxide Brayton cycle with an absorption heat transformer, Energy Convers Manag 251 (2022). https://doi.org/10.1016/j.enconman.2021.114992.

[9] I. - International Energy Agency, World Energy Outlook 2023, 2023. www.iea.org/terms.

[10] G. Wrochna, M. Fütterer, D. Hittner, Nuclear cogeneration with high temperature reactors, EPJ Nuclear Sciences & Technologies 6 (2020) 31. https://doi.org/10.1051/epjn/2019023.

[11] IAEA., Industrial Applications of Nuclear Energy., IAEA, 2017.

[12] V. Dostal, P. Hejzlar, M.J. Driscoll, High-performance supercritical carbon dioxide cycle for next-generation nuclear reactors, Nucl Technol 154 (2006) 265–282. https://doi.org/10.13182/NT154-265.

[13] S. Yun, D. Zhang, X. Li, X. Zhou, D. Jiang, X. Lv, W. Wu, Z. Feng, X. Min, W. Tian, S. Qiu, G.H. Su, Design, optimization and thermodynamic analysis of SCO2 Brayton cycle system for FHR, Progress in Nuclear Energy 157 (2023). https://doi.org/10.1016/j.pnucene.2023.104593.

[14] IAEA Nuclear Energy Series @, n.d. http://www.iaea.org/Publications/index.html.

[15] Clean Growth - Transforming Heating - Overview of Current Evidence, 2018.

[16] M.A. Fütterer, R. Pabarcius, S. Hübner, L. Pieńkowski, W. Brudek, P. Darnowski, M. Pawluczyk, B. Chmielarz, M. Šilhan, Nuclear process heat application options: Highlights from the European GEMINI+ project, Nuclear Engineering and Design 396 (2022). https://doi.org/10.1016/j.nucengdes.2022.111879.

[17] D. Prochazkova, J. Prochazka, V. Dostal, Resiliency of Industrial Complexes Powered by Small Modular Reactors, in: Research Publishing Services, 2023: pp. 1506–1513. https://doi.org/10.3850/978-981-18-8071-1\_p068-cd.

[18] V. Dostal, P. Hejzlar, M.J. Driscoll, The supercritical carbon dioxide power cycle: Comparison to other advanced power cycles, Nucl Technol 154 (2006) 283–301. https://doi.org/10.13182/NT06-A3734.

[19] N. Pardo, K. Vatopoulos, A. Krook-Riekkola, J.A. Moya, A. Perez, European Commission. Joint Research Centre. Institute for Energy and Transport., Heat and cooling demand and market perspective., Publications Office, 2012.

[20] M.A. Fütterer, R. Pabarcius, S. Hübner, L. Pieńkowski, W. Brudek, P. Darnowski, M. Pawluczyk, B. Chmielarz, M. Šilhan, Nuclear process heat application options: Highlights from the European GEMINI+ project, Nuclear Engineering and Design 396 (2022). https://doi.org/10.1016/j.nucengdes.2022.111879.

[21] V. Kindra, I. Maksimov, D. Patorkin, A. Rogalev, N. Rogalev, Thermodynamic Analysis and Optimization of Binary CO2-Organic Rankine Power Cycles for Small Modular Reactors, Energies 17 (2024). https://doi.org/10.3390/en17102377.