Applied Thermal Engineering 280 (2025) 128135

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Supercritical CO_2 power cycle control strategies: A review

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ARTICLE INFO

Keywords:
sCO_2 power cycle
Control strategies
Load-following
Start up
Shutdown

ABSTRACT

In recent years, the supercritical Carbon Dioxide (sCO_2) cycle has been considered a future advanced technology for power conversion because of its distinctive characteristics, such as compactness, high efficiency and flexibility in handling different heat sources. So far, most studies on sCO_2 cycles have focused on thermodynamics and dynamic modelling, with much less attention given to control systems. Effective control strategies are crucial for optimising performance and ensuring safety. This paper aims to address the gap in the existing literature through providing a detailed review of the control strategies for sCO_2 power cycles, including basic control strategies for startup/shutdown and off-design performance, combined control strategies, and advanced control strategies. The review shows that the combined control strategies approach and control strategies with AI/data-driven techniques are promising approaches, but further research is needed to understand their long-term effectiveness and how well they adapt to different operating conditions. The sCO_2 cycle could also work better if it used advanced control strategies currently proven in other systems, such as fuzzy PID, model predictive control, and fuzzy neural network adaptive controllers. These methods, proven effective in managing complex systems like micro gas turbines, may offer significant improvements for sCO_2 cycle performance.

1. Introduction

1.1. Background

The combination of increased aspiration for high living standards and population growth has led to increased demand on energy, especially electricity. Electricity generation is expected to be the primary method of energy consumption worldwide by 2050 [1]. However, despite the increasing demand for electricity, most countries' attempts and commitments to achieve net-zero emissions aim to reduce Carbon Dioxide (CO_2) emissions by embracing cleaner and more efficient power-conversion technologies. The effective approach to limit carbon emissions involves replacing fossil fuel-based energy systems with renewable alternatives such as solar, wind, biomass, and others. Many countries have committed to achieving carbon neutrality by the year 2050.

Aligned with international efforts, many developed countries have set out ambitious goals for both mitigating climate change and full reliance on clean energy. The European Union (EU) member states, developed a Climate and Energy Roadmap 2030, which prioritised a 55 % decrease in Greenhouse Gas (GHG) emissions and a 32 % integration of Renewable Energy Sources (RES) into the energy mix by 2030 [2]. In addition, the UK government released a net zero plan in 2023, which shows that the UK will reduce the GHG by 78 % in 2035 and this will be achieved by involving a renewable energy source such as wind and solar and nuclear energy [3]. Consequently, the energy systems in these countries are shifting towards decentralization, integration, and the interconnection of energy networks with the goal of achieving a higher adoption of renewable energy sources. Because solar and wind energy sources are intermittent and unpredictable, hybrid integrated systems that combine them with gas turbines or steam turbines are considered to be an effective option [4].

Nevertheless, attaining additional accomplishments remains challenging. For instance, in the conventional energy field, the energy efficiency is constrained by the performance of materials when exposed to extreme temperatures and pressures [5,6]. The cost of certain types of renewable energy is more than that of fossil energy, which poses a challenge to the widespread adoption and industrialization of renewable energy technology [7]. Hence, considering the aforementioned challenges, it is imperative to expedite the development of novel energy conversion technologies to achieve a step increase in efficiency and lower the costs associated with the power generation systems. The supercritical Carbon Dioxide (sCO_2) power generation technology has

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https://doi.org/10.1016/j.applthermaleng.2025.128135
Received 13 March 2025; Received in revised form 3 June 2025; Accepted 31 August 2025
Available online 16 September 2025

Nomenclature

Abbreviations

AFB	Auxiliary Fossil Fuel Backup
AFR	Air-To-Fuel Ratio
AGC	Automatic Generation Control
AI	Artificial Intelligence
ANNs	Artificial Neural Networks
BBP	Blade Back Side
BCV	Bypass Cooler
BFV	Backflow Valve
CCS	Coordinated Control Systems
CFPP	Coal-Fired Power Plant
CIP	Compressor Inlet Pressure
CIT	Compressor Inlet Temperature
CO_2	Carbon Dioxide
COT	Cooler Outlet Temperature
CS	Compressor Surge
CSP	Concentrated Solar Power
CTM	Constant Temperature Mode
DCS	Dual Control Strategy
DGS	Dry Gas Seals
DNNs	deep neural networks
DOC	Direct Oxy-Combustion
DRL	Deep Reinforcement Learning
ES	Extremum Seeking
ESC	Extremum-Seeking Control
ETES	Electric Thermal Energy Storage
EU	European Union
F-CV	Fuel Control Valve
FNN	Fuzzy Neural Network
FTM	Flexible Temperature Mode
GHG	Greenhouse Gas
GS-PID	Gain-Scheduled PID Controller
GWP	Global Warming Potential
HS	Heat Source
HTF	Heat-Transfer Fluid
IAE	Iterative Absolute Error
ICC	Intercooling Cycle
IGV	Inlet Guide Vane
ILC	Iterative Learning Control
IMC	Inventory Management Control
INV	Inventory Control
ITSE	Iterative Time Square Error
LBE	Lead-Bismuth Eutectic
LFR	Lead-Cooled Fast Reactor
LMPC	linear model predictive controller
MARS	Multi-Dimensional Analysis of Reactor Safety
MCIP	Main Compressor Inlet Pressure
MCIT	Main Compressor Inlet Temperature
MCOP	Main Compressor Outlet Pressure
MGT	Micro Gas Turbines
MS	Molten Salt
ODP	Ozone Depletion Potential
OFB	Oil-Fired Boiler
ORC	Organic Rankine cycle
P	Electric Power Output
PB	Pressure Balance
PC	Pre-Compression Cycle
PCC	Partial-Cooling Cycle
PCM	Predictive Control Model
PI	Proportional–Integral
PID	Proportional–Integral–Derivative
R-CV	Recirculation Control Valve
R-THV	Recuperator Throttle Valve
RC	Recompression Cycle
RC-DRC	Recompression- Dual Recuperated Cycle
RES	Renewable Energy Sources
RL	Reinforcement learning
RS-BYP	Rotational Speed-Bypass
RS-INV	Rotational Speed-Inventory
RS-TIP	Rotational Speed-Turbine Inlet Pressure
RS-TIT	Rotational Speed-Turbine Inlet Temperature
SCBC	Supercritical Carbon Dioxide Brayton Cycle
SCBC-P	SCBC Pressure
SCIEL	sCO_2 Integral Experimental Loop
sCO_2	Supercritical Carbon Dioxide
sCO_2-DHRS	sCO_2 Decay Heat Removal System
SP	Load Setpoint
SPT	Solar Power Tower
SR	Split Ratio
SR-RC	Single-Recuperator Recompression Cycle
SRC	The Simple Recuperated Cycle
TAC	Turbomachinery And Compressor
TAC-SP	TAC Speed
TAC-TH	TAC Thrust
TBV	Turbine Bypass Valve
TEGT	Turbine Exhaust Gas Temperature
TES	Thermal Energy Storage
TF	Thrust Forces
THBV	Turbine And Heater Bypass
THV	Throttling Valve
TIP	Turbine Inlet Pressure
TIT	Turbine Inlet Temperature
TOT	Turbine Outlet Temperature
VIGV	Variable Inlet Guide Vanes
WHR	Waste Heat Recovery

Symbols

$\dot{\mathbf{m}}_{\mathbf{co_2}}$	sCO_2 Mass Flowrate (Kg/s)
$\dot{\mathbf{V}}_{\mathbf{co_2}}$	Volumetric Flow Rate (m^3/s)
$\mathbf{G_{ES}}$	Extraction Steam Flow
$\mathbf{G_{hot}}$	Heat-Conducting Salt Flow
$\mathbf{m_{MS}}$	MS Mass Flowrate (Kg/s)
N	Shaft Speed (rpm)
P	Electric Power Output (MW_e)
P_{ms}	Main Steam Pressure

Greek letters

$\boldsymbol{\mu}_{\mathbf{CF}}$	Coal Flow
$\boldsymbol{\mu}_{\mathbf{TG}}$	Turbine Governor Valve Opening

Subscripts

CHX	Compact Heat Exchangers
comb	Combustor
HTR	High Temperature Recuperator
Pre	Pressurizer

recently sparked significant debate in the solar, nuclear, and natural gas power plant industries due to its potential for high efficiency and lower cost. The advantages of this technology have been initially confirmed through theoretical and experimental analyses.

The sCO_2 cycle operates under conditions where the pressure and temperature of the working fluid (CO_2) are above the critical point (31.1 °C, 7.38 MPa). The remarkable efficiency and distinctive characteristics of sCO_2 cycle are a result of the outstanding thermodynamic properties of sCO_2. The physical properties of CO_2 close to the critical point or pseudo-critical point (a state where the fluid is at a pressure greater than the critical pressure and at a temperature that corresponds to the highest specific heat) exhibit significant nonlinearity [8]. In the vicinity of the critical point or pseudo-critical point, carbon dioxide exhibits properties that are intermediate between those of a gas and a liquid. Specifically, its viscosity is lower than that of a liquid, while its density and specific heat capacity are higher than that of a gas. The CO_2 fluid is frequently maintained close to its critical point at the compressor inlet to optimise the equilibrium between density, viscosity, and specific heat capacity. This allows for the utilization of its high density and low compressibility factor, resulting in reduced compression power requirement [9]. Furthermore, the high density of the substance aids in minimizing the size of turbomachinery, resulting in cost savings during construction [10]. In addition to the benefits of high efficiency and small components, CO_2 is non-toxic, non-flammable, and generally non-corrosive in its dry form although it can become reactive and acidic in the presence of moisture. While CO_2 offers many advantages, it is important to note that pure CO_2 is not particularly cheap. Additionally, it is worth noting that this substance is environmentally beneficial, as it has an Ozone Depletion Potential (ODP) of zero and a Global Warming Potential (GWP) of one over a period of 100 years [11]. These benefits render CO_2 very suitable as a working substance for a closed power cycle.

Furthermore, sCO_2 systems have been studied for use in several applications in the power production sector, including nuclear, Concentrated Solar Power (CSP), geothermal, and Waste Heat Recovery (WHR) [12]. Even in power plants that use fossil fuels, sCO_2 systems have potential benefits compared to traditional steam and gas turbine technologies. These systems can enable the use of carbon capture and storage technology [13,14] and can also adapt to and handle the wide range of operating conditions caused by the growing use of renewable energy sources in the energy mix [15].

1.2. sCO_2 power cycle layouts

The fundamental components for the sCO_2 cycle consist of expansion (turbine) and compression (compressor), while the key thermodynamic processes are recuperation, cooling, and heating. To achieve greater thermal efficiency, additional processes such as multi-stage compression, re-heating, and other thermodynamic processes are incorporated. The above processes can be combined to create various sCO_2 cycle layouts, including the Simple Recuperated Cycle (SRC) [16], Pre-Compression Cycle (PC) [16], Recompression Cycle (RC) [17], Partial-Cooling Cycle (PCC) [18], and Intercooling Cycle (ICC) [19], along with their corresponding re-heating layouts [20,21]. Consequently, researchers have analysed all the previous sCO_2 cycle configurations for various applications [22,23,24]. The simplest arrangement is the basic recuperated Brayton cycle, which is similar to a conventional recuperated Brayton cycle. The problem with this arrangement is that it faces an internal pinch point that restricts total heat transfer, and the hot and cold streams of the recuperator have significantly different heat capacities because of the substantial variation in physical properties close to the critical point [25]. Dostal et. al [23] proposed the use of the recompression Brayton cycle, which incorporates two recuperators (RC-DRC- SCBC) and divides a portion of the cold stream before heat rejection. This divided portion is then compressed by a second compressor that operates in parallel with the main compressor. The divided fluid is subsequently reintroduced following the low-temperature recuperator. This method allows for a more accurate alignment of the capacity rates between the hot and cold streams, resulting in a higher level of heat recovery.

Various alternative cycle configurations have been examined for CSP, such as the simple Brayton cycle with reheat, the recompression Brayton cycle with reheat, the partial cooling cycle with recompression and reheat, and the recompression cycle with inter-cooling and reheat of the main compressor [24]. Although partial cooling and recompression with main compressor inter-cooling are appealing choices for CSP systems to achieve high efficiency, the majority of the sCO_2 industry has shifted its attention to the recompression Brayton cycle. This is mainly due to its ability to achieve high efficiency without introducing significant complexity [23,26].

Among the various arrangements of sCO_2 power cycle layouts, five specific configurations have arisen, each possessing unique characteristics and performance attributes. The layouts consist of the SRC [16], the PC [27], the RC [17], the PCC [28], and the (ICC) [19]. In order to figure out the most efficient layout, a study conducted a comparison of these five configurations, using the SRC as a baseline. The study clearly showed that the recompression and inter-cooling configurations are the most efficient methods for improving cycle efficiency, resulting in remarkable increases of 3.51 % and 3.93 %, respectively, given a certain turbine inlet pressure of 25 MPa and turbine inlet temperature of 565 °C [29]. Expanding on these findings, the implementation of a multi-stage compression arrangement sets the ground for the creation of the tri-compression sCO_2 cycle, which achieves an impressive efficiency rating of 52.54 % (620 °C/30 MPa). This accomplishment highlights the intricate balance between thermodynamic efficiency and system complexity, stimulating additional investigation and discourse within the discipline.

1.3. sCO_2 power cycles dynamic models

Dynamic modelling functions as a vital instrument for evaluating and enhancing the performance of different power cycle layouts. The models are classified into three distinct levels of increasing complexity: design point, off-design, and transient analysis.

At the design point level, the specifications of cycle components are analysed in detail, with precise calculation of steady-state inlet and outlet conditions, heat duty, and power requirements. By conducting a thorough investigation, manufacturers can customise the design of equipment to match specific performance requirements, which serves as a basis for evaluating its performance under different conditions. After the equipment designs are completed, manufacturers give additional information that help in predicting the performance of the cycle under off-design steady-state situations. This stage frequently entails the application of turbomachinery maps and heat exchanger performance factors to enhance performance predictions.

Nevertheless, the intricacy of power cycles goes beyond their stable operation, requiring the incorporation of transient analysis. Transient analysis explores dynamic circumstances, including start-up, shutdown, and emergency situations, providing insights into the behaviour of cycles under changing conditions. To effectively predict cycle dynamics during transient occurrences, this sophisticated modelling approach necessitates a more comprehensive understanding of information such as valve trims (the internal components of a valve that control flow characteristics), opening times, and turbomachinery inertia. Existing literature indicates a lack of studies specifically dedicated to the start-up and shutdown of Supercritical Carbon Dioxide Brayton Cycle (SCBCs) for WHR applications. On the other hand, a greater number of studies are available for the start-up and shutdown of SCBCs for nuclear power and CSP applications. To ensure the system operates safely and efficiently during these transitional phases, it is necessary to conduct a comprehensive analysis of the dynamic process characteristics, as well as establish appropriate control strategies.

1.4. sCO_2 power cycles control strategies

During the actual operation, effective control strategies are essential to ensuring that SCBC operates safely and efficiently through different operational conditions, such as load following, start-up, and shutdown. These strategies can be broadly categorised as valve control, heat source control, inventory control, and turbomachinery rotational speed control, each with distinct performance characteristics. By combining several control strategies, it is possible to enhance the system's efficiency; however, this will increase the system's complexity. Meanwhile, an alternative approach to improving the control system is to incorporate Artificial Intelligence (AI) into the control system. Although other systems frequently use AI techniques such as Artificial Neural Networks (ANNs) and Deep Reinforcement Learning (DRL) to optimise operation and efficiency, SCBC has not yet widely adopted these techniques, which could potentially lead to significant improvements in control performance.

The control strategy for sCO_2 power cycle with various heating sources (such as CSP, WHR, nuclear, and fossil fuels) is a highly significant research topic. This is especially true when the SCBC system encounters varying load demands, heat sources, start-up and shutdown procedures, emergency situations, and failure states. Additionally, it is crucial to test the control strategy's effectiveness in mitigating the propagation of failures. While implementing the SCBC system in nuclear or coal-fired power plants, the system must adjust its load in response to changes in demand.

In contrast, whether using solar energy or industrial waste heat as heat sources, the SCBC system needs to be able to handle fluctuations in heat sources. Research on control strategies for the sCO_2 power cycle has not been extensively conducted. However, the academic research, such as journal papers, conference proceedings, and book chapters, etc., on this topic has started to step up since 2013, as shown in Fig. 1. The majority of the academic research conducted on this topic has originated in China (CN&CNR), the United States of America (USA), and other countries such as Germany, Italy, etc.

However, based on the author's knowledge, there is no specific review available for this particular topic. However, specific review studies that examine the sCO_2 power cycle only offer a brief summary of the control strategies for sCO_2 [8,30,31,32]. An extensive analysis of the control strategy of SCBC is essential for researchers and industry developers to understand the current level of development. This comprehensive perspective/analysis enables researchers and industry developers to make logical choices. Therefore, this work aims to fill the information gap in the existing literature by providing a thorough analysis of research on dynamic control strategies for SCBC.

This paper provides an overview of all control strategies for SCBC in Section 2, accompanied by detailed explanations. Section 3 consists of all previous studies on the conventional control strategy for SCBC. Section 4 then delves into an extensive literature review on SCBC's implementation of a combined control strategy. Section 5 provides a comprehensive literature review of the advanced control strategy for SCBC, and at the end of each section there is a summary of all previous studies. Finally, this paper concludes by presenting conclusions, challenges, and potential paths for further research.

2. Overview of sCO_2 power cycle control strategies

As aforementioned, effective control strategies in various operational conditions, such as load following, start-up, and shutdown, are necessary for the sCO_2 power cycles to operate safely and efficiently. Below-mentioned control strategies are employed to control some of the most important parameters involved within the sCO_2 power cycle, including Main Compressor Inlet Temperature (MCIT), Main Compressor Inlet Pressure (MCIP), compressor surge or chocking, Turbine Inlet Temperature (TIT), and turbomachinery speeds. Meanwhile, these parameters can be kept under control using different control strategies and various manipulating variables, such as turbomachinery speed, a cold and heat source, valves, etc. Those can further be combined or improved by AI

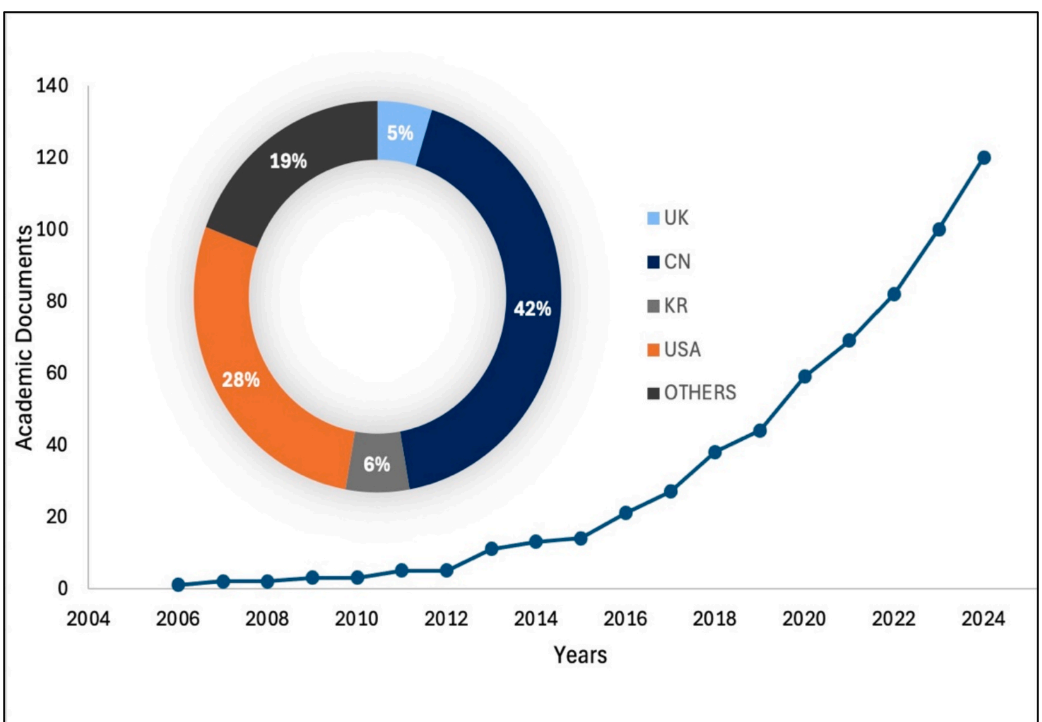

Fig. 1. Academic research growth for control strategies for the sCO_2 power cycle. Data compilation from the Scopus, Google Scholar, and Espacenet global databases from January 2006 to November 2024. The doughnut charts represent the total outputs throughout the surveyed period, while the legend indicates the shares for the People's Republic of China (CN), the United States of America (US), the Republic of Korea (KR), the United Kingdom (UK), and the remaining parts of the world (OTHER).

technologies to further enhance the performance of the control system. However, it is important to note that as the size and complexity of the control strategy increase, the control system's manageability becomes increasingly challenging. In the following subsections, a detailed description of some major control methods for load-following, start-up, and shutdown is presented. These include inventory control, heat and cold source control, turbomachinery rotation speed control, valve control, and control strategies enhanced by using AI.

All the existing works about the control strategies mostly focused on SRC-SCBC and RC-SCBC. Fig. 2 illustrates all the control strategies previously used on SRC-SCBC, RC-SCBC, and RC-DRC-SCBC, along with the manipulated parameters used in each strategy.

2.1. Inventory control

Inventory control regulates the system load by removing or adding the working fluid from the system, and there are two methods proposed by Dostal et. al to implement the inventory control strategy [23]. The first and basic approach is removing the working fluid from the high-pressure side or at the compressor outlet to the tank via V2 or adding it through V4 to the low-pressure line at the cooler inlet, as illustrated in Fig. 2. The basic principle that governs this strategy is modification of system load by variation of flow rate of the working fluid being circulated. This Inventory control can optimise thermal efficiency during load-following operations, but it has two key limitations: a sluggish response rate and a limited capacity of the inventory tanks. To address the sluggish response associated with the basic inventory control strategy, Dostal et.al [23] proposed a second inventory control strategy. This second method also regulates fluid flow through the inlet (V17) and the outlet (V18) valves that are connected to the high-pressure side at the compressor outlet and a boost compressor, as illustrated in Fig. 3. The boost compressor employed to increase the fluid pressure adds to the cycle from the tank during the discharge process; however, this process is more complex.

Furthermore, the inventory control strategy is used to control MCIP, and this parameter is considered one of the crucial parameters for the main compressor inlet conditions, and the second parameter is the MCIT, which will be explained in the next section. The main CO_2 compressor normally operates near the critical point of CO_2 at 31.3 °C and 7.38 MPa, where the physical properties of CO_2 change dramatically to remarkably affect the system performance of the whole system. Therefore, it is very important to control the status of the compressor inlet in order not to make the system enter the subcritical area. Usually, the MCIP is controlled via the discharge and the charge of the working fluid. Additionally, during the normal operation of the cycle, the pressure loop is a function of the CO_2 mass [33]. The recuperator throttle valve (V8 in Fig. 2) controls the MCIP.

During dynamic operations, it is crucial to control the compressor surge, a phenomenon that results from a shortage of mass flow rate through the compressor. This phenomenon can lead to abnormal compressor vibration, reduce cycle efficiency, and even cause degradation in the turbomachinery. So, to protect the compressor from this phenomenon, the mass flow rate through the compressor needs to increase, and this can be happened by either controlling the turbomachinery rotational speed, using throttling control valves such as V1 and V9, or using a recircuiting valve such as V5, as shown in Fig. 2.

2.2. Cold and hot source control

The TIT is an important control factor that can impact both the power output and the safety of the system. Additionally, there are several strategies to control the TIT, but the common strategy is the hot source control strategy, which is employed to regulate the TIT by adjusting the position of the heat exchanger valve (V16 in Fig. 2). However, in cases where the TIT is regulated by alternative means or disregarded, the adjustment of the heat source can be utilized to govern the input heat into sCO_2 power cycle in order to modify the system's output power.

On the other hand, the cold source is used to control MCIT, which is typically controlled by manipulating the mass flow rate of the cold source [34]. The control strategy for MCIT begins by comparing the actual MCIT with a reference value. If there is any difference between these two values, adjustments are made to the mass flow rate of the cold source by adjusting the position of the cooler valve (V7 in Fig. 2) or by changing the rotating speed of the cooler pump. Furthermore, coupling the control strategy for regulating the mass flow rate of the cold source with the cooler bypass control strategy (V6 in Fig. 2) provides a more effective approach to controlling MCIT [35,36]. It is particularly suitable to use this combined strategy when there is a considerable anticipated reduction in MCIT. In such situations, relying just on the cooler bypass

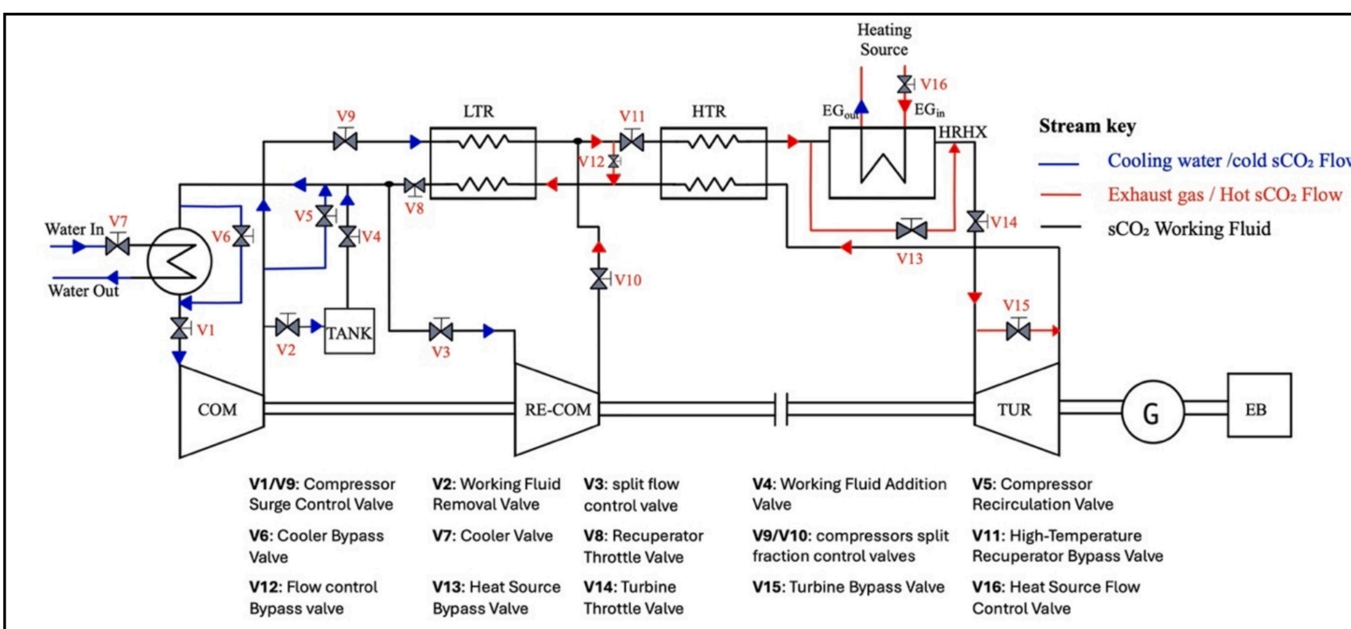

Fig. 2. Overview of previous control strategies for SRC-SCBC and RC-SCBC cycles.

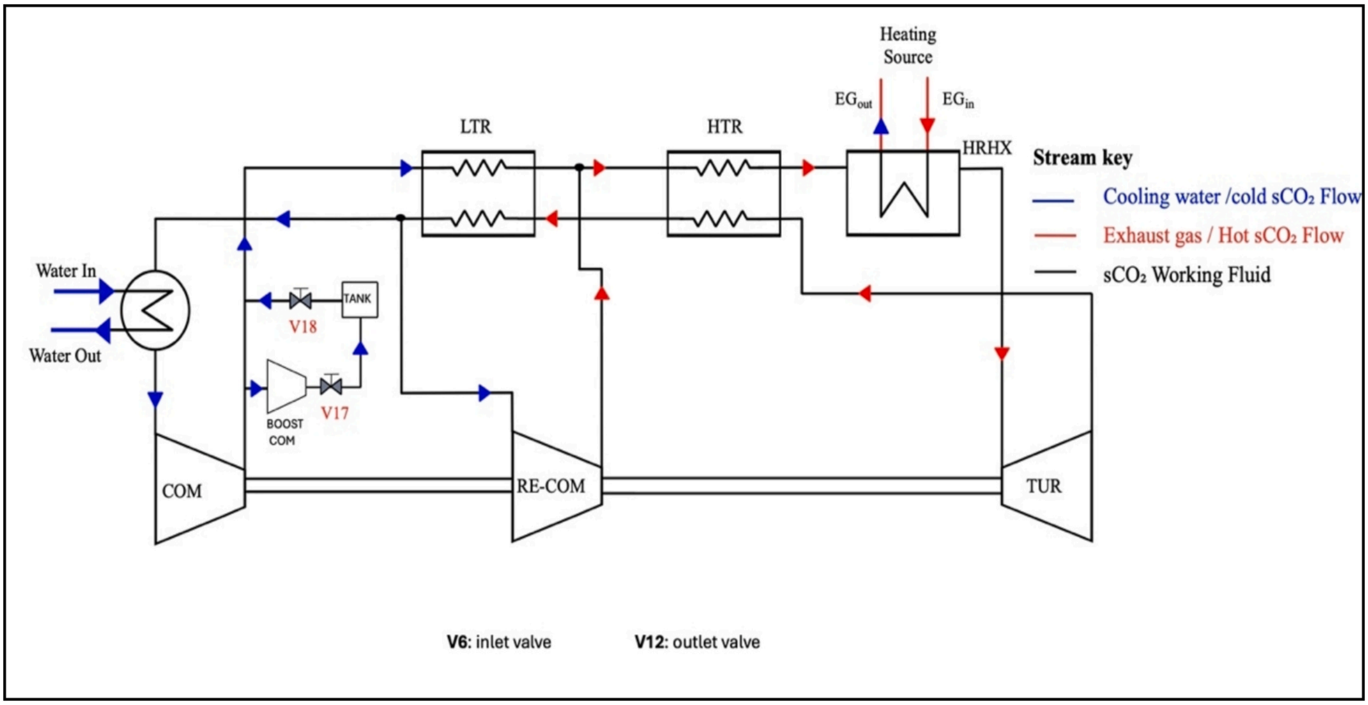

Fig. 3. Second inventory control strategy for SRC-SCBC and RC-SCBC cycles.

control strategy may not be beneficial, although the cold source mass flow rate control strategy remains suitable [37].

2.3. Turbomachinery speed control

Regulating the speed of the compressor can alter the rate at which CO_2 flows and the ratio of pressure; thus, the power of the system can be adjusted. The speed of the turbine-compressor is regulated by adjusting the position of the compressor recirculation valve (V5). This control mechanism is typically better suited for turbine and compressor systems that are not coaxial and would not be suitable for large systems. This adjustment is done using a Proportional–integral (PI) or Proportional–integral-derivative (PID) controller to accurately match the desired speed. Simultaneously, the heat source power is regulated to ensure a consistent temperature at the entrance of the turbine.

2.4. Valve control

The control of valve performance with rapid dynamic response involves the management of both throttle valve and bypass valve. Valves offer a common purpose of altering the flow area of the working fluid, which in turn reduces or prevents the flow. This adjustment directly affects the system's heat absorption and power output. Certain valves exhibit optimal performance when they are either fully open or totally closed. Others function as flow control devices, regulating the flow to achieve a specific pressure. Turbine bypass valve, turbine throttle valve, heat source bypass valve, and compressor bypass valve (V15, V14, V13, V5 in Fig. 2), are commonly employed to regulate the system load. Additionally, the bypass valves can be strategically positioned in several areas, including turbine bypass control, core bypass control, and higher cycle bypass control [38].

As aforementioned, the TIT is an important control factor that can impact both the power output and the safety of the system. There are several ways to control the TIT, such as altering the heat source mass flowrate (V16 in Fig. 2), adjusting different valves, adjusting inventory tanks, and adjusting the compressor speed [34,39,40]. Usually, a turbine bypass control valve (V15 in Fig. 2) regulates the mass flowrate for CO_2 via the heater to control the TIT [41,42].

The previous control parameters were considered essential in the most previous research, but there were other control parameters that can be considered minor control parameters during the system operation, and these control parameters are heat exchanger inlet temperature, flow split fraction, and compressor speed. Typically, the high-temperature recuperator bypass valve (V12 in Fig. 2) regulates the temperature at the heat exchanger's entrance, enabling more effective reactor control [36]. Several controlled parameters, including valve placement and compressor speed, can control the flow-split fraction to optimize the system's efficiency. However, previous research has not placed much emphasis on this aspect. The Split Ratio (SR) can be controlled by valves located at the main compressor and recompressor outlets (V10, V9 in Fig. 2) or by adjusting the speed of the compressor [38]. The compressor is often powered by either a shaft motor or a separate turbine, allowing it to be regulated by the motor's speed or the compressor recirculation valve [43].

2.5. AI – Advanced control strategies

The majority of published research has concentrated on basic control strategies. All of the control strategies mentioned above whether in simulation studies [34,44] or experimental studies [45,43], have been implemented using a PID or PI controller. However, such control strategies have a limited degree of efficiency due to the use of a PI or PID controller, as it has a notable limitation in the presence of an sCO_2 power cycle. Specifically, the PID reacts very sensitively to nonlinearity and rapid changes in the parameters near the critical point, which can lead to system instability or inaccurate control systems during transient events such as startup and shutdown. To address these limitations, previous research in sCO_2 control strategies proposed a gain-scheduled PID, and other research in gas cycles used Fuzzy-PID [46,47,48]. These adaptive PID methods offer improved robustness systems particularly during startup and shutdown, as they adjust the controller parameters in real time based on the system condition, however, those methods are still underexplored for sCO_2 power cycles.

Meanwhile, a more advanced method is to combine the PID controller with AI techniques, as mentioned previously. So, one of these AI techniques is ANNs, which are computational models that replicate the neural structure of the human brain. It has the ability to learn and understand intricate linkages within the sCO_2 cycle. ANNs utilize historical and real-time data to make predictions about system behaviour and adjust control settings in order to improve performance. On the other hand, DRL algorithms facilitate the independent acquisition of optimal control strategies by engaging with the surroundings through a process of trial and error, with the goal of maximizing the total rewards obtained.

The DRL is a combination of the DNNs (Deep Neural Networks) and RL (Reinforcement Learning), and actually the DRL is capable of dealing with complex and nonlinear data, which is one of the DNNs advantages, and on the other hand, the RL supports the DRL with the decision-making ability (figuring out the best control strategy through trial and error, even in stochastic environments). However, these features enable the DRL to effectively address a variety of complex control problems. In DRL, an agent acquires an optimal policy, which is a strategy for action decision-making, through interaction with an environment aimed at maximising cumulative rewards. Generally, a DNN models the policy and adjusts it based on feedback from these interactions. In online DRL, the agent interacts directly with the sCO_2 cycle simulator or physical system, continuously optimising its policy based on real-time feedback. This strategy enables swift adaptation; however, it poses risks in high-pressure systems such as sCO_2, owing to possible safety and equipment issues. Alternatively, offline DRL utilises a pre-collected dataset of operational data from the sCO_2 cycle to train the policy. This removes the necessity for live experimentation and facilitates safe policy development, making it particularly appropriate for safety–critical and high-cost contexts such as sCO_2-based power systems. Offline DRL provides a viable approach for implementing intelligent control in sCO_2 applications, effectively reducing operational risk and with an affordable cost.

Meanwhile, using DRL for the sCO_2 power cycle, remains underexplored, but a study was conducted comparing the use of a traditional PID controller and offline DRL control to control the superheat of the Organic Rankine Cycle (ORC) with Toluene as the working fluid, and it was discovered that the average setpoint tracking error was only 0.19 K for the DRL system, while the traditional PID controller was 2.16 K [46].

Therefore, the successful application of DRL in ORC can be a useful reference for other dynamic systems, such as SCBC. The following Fig. 4 is driven from [46], with adjustments to show the capability for using the DRL controller with the sCO_2 power cycle. Fig. 4a illustrates the direct use of DRL in controlling the TIT to attain goal power, enhance performance, and safeguard the turbine. The DRL controller first obtains the system state of the sCO_2 power cycle as an observation, encompassing characteristics such as temperatures and pressures. In the second step, the DRL controller acts based on these observations and determines the optimal method to control TIT, such as adjusting the turbomachinery speed to regulate the CO_2 mass flow rate and maintain the desired TIT. After the action step, there is a reward used as input to RL to encourage the DRL controller to improve the tracking performance, and a higher reward means good performance and the value of the TIT is near the desired value, and the lower reward is the opposite. Moreover, during the tuning, the DRL controller uses this feedback to refine its policy (DNNs) to enhance future performance.

Nonetheless, the policy of the DRL comprises an DNN, which potentially contains hundreds of thousands of weights and biases, along with a nonlinear activation function. A minor alteration may trigger an entirely different configuration of neurone activation, yielding an undesirable outcome; thus, ensuring the policy's robustness under all conditions is challenging. The agent may undertake irrational acts given specific untrained circumstances. Evaluating a greater number of situations mitigates risk; yet, it is unfeasible to test all conditions to guarantee a 100 % accurate policy. A DRL-based PID control technique is presented to enhance the resilience of the controller, as illustrated in Fig. 4b.

The observation and the reward for the strategy in Fig. 4b are the same as in Fig. 4a, but the action in Fig. 4b is the PID parameters, so in this case the DRL is used continuously to optimise the PID controller to achieve the desired TIT by changing the PID gains.

By incorporating ANNs and DRL into control strategies, sCO_2 power cycles could attain accurate management of temperature and pressure, respond to fluctuating load needs, and guarantee stable and efficient operation, particularly during transitional periods such as start-up and shutdown. These advanced methods tackle the specific difficulties presented by the sCO_2 power cycle's susceptibility to operational parameters, ultimately improving energy conversion efficiency and system reliability.

In addition, some researchers have combined Extremum-Seeking Control (ESC) with the inventory control technique to reduce the potential risks involved in operating the plant with a constant CO_2 inventory. ESC, a model-free adaptive control technique, has gained considerable interest in the past few years. The system takes continuous readings of a plant's performance function and processes them with the right filters to get gradient estimates of the function with respect to the steady-state inputs to the plant. A complex optimization algorithm specifically employs this data to finely adjust the plant inputs, aiming to achieve convergence towards optimal plant functioning. Plants with inputs in multiple dimensions can also apply this strategy. The recent use of ESC has effectively improved operational efficiencies and maximized power generation in diverse applications, such as fuel cell systems [47], solar photovoltaic power systems [48], chilled-water system optimization [49], and wind-turbine power optimization [50].

3. Basic control strategies for SCBC

During transient and off-design operations, the SCBC often needs to adhere to the load demand and operate safely and efficiently. Various control systems for load following, start-up, and shutdown are presented in the following subsections, each with distinct performance characteristics. As previously mentioned, the main control strategies for the SCBC are valve control, heat source control, inventory control, and turbomachinery rotation speed control. This section provides extensive information on control strategies for load-following, start-up, and shutdown operations. Current strategies for control in the literature mostly focus on SR-SCBC (simple-recuperated SCBC), RC-DRC-SCBC (Recompression-Dual Recuperated), and RC-SCBC (recompression SCBC) cycles.

3.1. Startup/shutdown dynamics model

In a numerical study, Marchionni et al. [51] investigated the dynamic behaviour and control strategies of bottoming cycle 50 KW_e SR-SCBC heat-to-power systems. Using a 1D modelling approach, the sCO_2 system was examined, focussing on start-up, shutdown, and transient heat load profiles. It was found that the system inventory was effective for Turbine Inlet Temperature control (TIT). The study highlighted the flexibility of the sCO_2 system and proposed an inventory (INV) control strategy with a PI controller for regulating TIT during transients. In addition, considering the potential performance drawbacks under certain heat load control strategies, they suggested that further exploration into a hybrid control strategies may offer opportunities for achieving even more efficient control.

Considering Marchionni et al.'s focus on the inventory control strategy, Liese et al. [34] expanded on the concept of inventory in their transient simulations for a 10 MW_e RC-DRC-SCBC pilot plant and a natural gas-fired furnace or combustor(comb) was used as the external heat source. During the load-following process, start-up, and shutdown at 4 MW_e, the control variables are the TIT/ Turbine Exhaust Gas Temperature (TEGT), SCBC pressure (SCBC-P) and MCIT, which are controlled by the inventory control strategy and Bypass Cooler (BCV) control strategy, respectively. This study also used Fuel Control Valve (F-

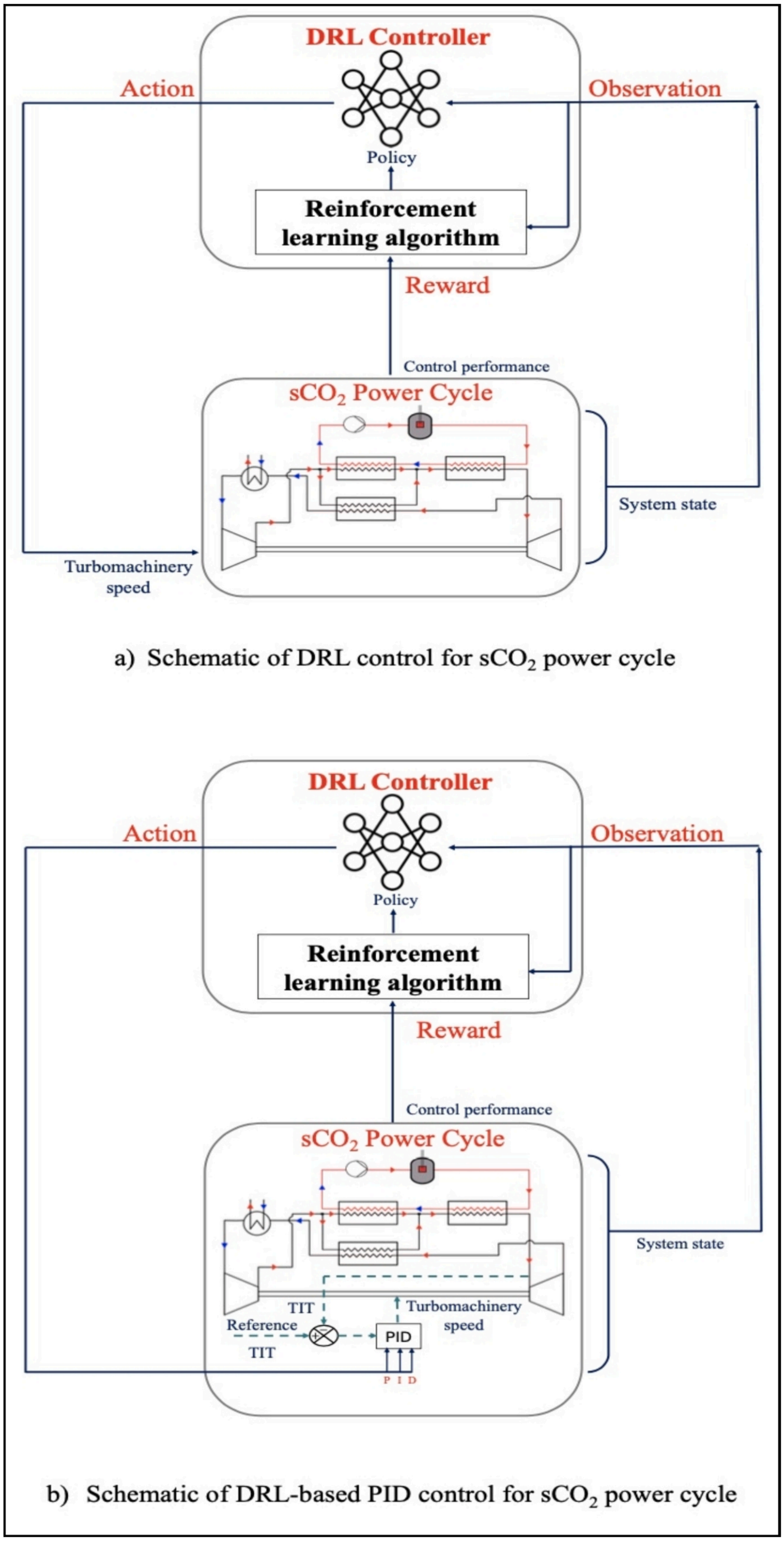

Fig. 4. Based control method for sCO_2 power cycle.

CV) in order to control Air-to-Fuel Ratio (AFR), a Recirculation Control Valve (R-CV) used to protect the Compressor Against Surge (CS), TEGT control, with load setpoint-based gain scheduling (EGT-SP), which changed the outputs of the temperature controller based on the current load to make it more responsive. This work discusses the operation and control of load following, specifically focusing on reducing the load from its design value to a part load and then increasing it again. The results indicate that inventory control enables accurate monitoring of the load. Numerous researchers, including Carstens [38], have demonstrated that inventory control is a very efficient method to control the load. However, its long response time and narrow range of load changes limit the effectiveness of the inventory control strategy.

Expanding these transient control strategies, Olumayegun and Wang [41] conducted a study on transient modelling and control system design for a Single-Recuperator Recompression (SR-RC) SCBC and the load was 5 MW_e, aiming at industrial waste heat recovery. A steady-state simulation was undertaken, and heat exchanger sizing was based on cement industry exhaust gas data. A dynamic model was developed using the MATLAB/Simulink and the control strategies used in this study included the implementation of a Throttling Valve (THV) control strategy to control Compressor Inlet Pressure (CIP) by the Recuperator Throttle Valve (R-THV), as well as the regulation of the MCIT by using the BCV control strategy and finally the TIT control by bypass valve control strategy.In addition, a PID controller was used in all strategies. The study revealed a predicted thermal efficiency of 33 %, an effective temperature profile matching between CO_2 and exhaust gas and emphasised the advantages of maintaining a constant CO_2 mass flow rate for optimal waste heat recovery, as well as allowing the TIT to vary with the change in the WHR mass flowrate. However, the study would be enhanced by incorporating a wider range of control strategies or hybrid control strategies and verifying the steady-state simulation results with experimental data to strengthen the reliability and practicality of the findings.

An extensive experimental analysis of a 300 kW_e RC-DRC-SCBC with Oil-Fired Boiler (OFB) heat source was conducted by Li et al. [52]. The analysis involved the utilization of integrated high-speed Turbomachinery and Compressor (TAC) units. Multiple control strategies were implemented as a result of the investigation to ensure stable and secure operation. These strategies comprised PID controllers for MCIT control via a cooler control strategy, a Turbine Bypass Valve (TBV) control strategy to control TIT, a TAC speed (TAC-SP) control system, a TAC Thrust (TAC-TH) control strategy used to minimise Thrust Forces (TF) via adjusting Pressure on the Blade Back Side (BBP), and finally an inventory control strategy to control MCIP. Results showed that closing bypass valves during start-up effectively controls TAC thrust, reduces compressor inlet temperature, and regulates blade back pressure. Additionally, closing the turbine bypass valve after reaching a supercritical state prevents system surge. However, precise control of water flow or compressor inlet pressure is necessary to avoid the main compressor entering the two-phase zone during inlet temperature regulation.

Building upon Li et al.'s experimental approach, Wang et al. [53] investigated control strategy and limitations involved in the shutdown and start-up procedure of a RC-DRC-SCBC. In addition, they utilised an inventory control strategy to manage the MCIP and implemented a Backflow Valve (BFV) to limit surge, and to regulate the MCIT, the BCV was used. A PI controller was employed in all these strategies. The study highlighted the need to simultaneously modify the rotational speed of Turbine-and-Compressor 1(TAC1) and Turbine-and-Compressor 2 (TAC2) to prevent significant changes in system parameters and retain control over the surge margin. The authors highlighted the significance of regulating the rate at which temperature changes occur by consistently modifying the rate at which fuel is changed. It was discovered that augmenting the mass flow rate through the injection of working fluid was more efficient than simply modifying TAC speeds or fuel during a cold start. The study emphasized the necessity of synchronized regulation of the heat source and TAC speeds to prevent subcritical situations and guarantee seamless operation. Although the study offered useful insights, putting these ideas into practice necessitated advanced control systems and experimental validation, which the authors intended to pursue in future research.

Similarly, Conboy et al. [54] conducted a comprehensive analysis of the control strategies implemented in a sCO_2 recompression Brayton cycle test facility. It emphasizes the critical importance of an initial CO_2 fill, which is approximately 100 kg, in order to achieve design conditions and avoid two-phase conditions at the compressor inlet. This investigation emphasizes the importance of a turbine bypass system to preheat the hot leg and prevent flow reversal, as well as a scavenging pump system to maintain lower film pressures, thereby reducing frictional losses. The heater bank's operation is meticulously controlled, with a gradual increase in temperature to control CO_2 passage through the turbines. An emphasis is placed on the importance of ongoing speed adjustments to prevent surge or stall conditions, with a particular focus on the parameters of heat sink control. It was highlighted that operational stability and bearing temperature management were obstacles despite the implementation of these measures, which resulted in a maximal power output of 15 kW_e. The study emphasizes the intricacy of preserving stability in high-temperature, high-speed turbomachinery systems, offering valuable insights into the nuanced control necessary for their efficient operation.

Following a different approach, Luu et al. [55] developed a successful control strategies and start-up scheme for a 2 MW_e solar-assisted RC-DRC-SCBC with an Auxiliary Fossil Fuel Backup (AFB) installed in parallel with the solar block. An additional shaft equipped the recompressor with an electric motor. Furthermore, four PI control loops were proposed for stable operation: a bypass air cooler control to regulate the MCIT, a Heat Source (HS) control to maintain the TIT at 600 °C, a Pressure Balance (PB) method using two throttling valves, and an inventory control strategy to adjust the SR between the two compressors. The start-up scheme had four phases: first, running only the main compressor with the turbine and filling sCO_2 from the inventory tank; second, maintaining phase one conditions but turning on the cooler and stopping the filling process; third, activating the recompressor after steady state to pump sCO_2 to the high-pressure side of the cycle; and fourth, operating the cycle in a closed loop without pumps or filling sCO_2. The results showed that sealing the cooler for a certain time boosted MCIT, ensuring supercritical conditions. To improve system efficiency and reliability, future studies should optimize these control techniques in different operational settings and integrate advanced control algorithms.

Meanwhile, Kriz et al. [56] conducted a numerical study on five control strategies for the Sofia 1MW_e SR-RC-SCBC. Moreover, the selected simulations, nominal steady state and power turbine start-up, were described in this paper to show the capabilities of the numerical model. The five control strategies encompassed controlling the MCIP through the use of a pressurizer (Pre), controlling the MCIT via a BCV, governing the Main Compressor Outlet Pressure (MCOP) through a THV located at the compander turbine inlet or a bypass valve at the turbines, controlling the TIT by adjusting the parameter for the heating source, and ultimately controlling the output power by means of a control valve at the power inlet turbine. However, this control loop was not yet used in simulations. The result reveals that careful manipulation of turbine valves in conjunction with pressurizer operation is crucial for optimal control. Also, the initial amount of CO_2 in the pressurizer affects its behaviours during start up. Despite the significant output of this numerical model, there is still a need to enhance and apply more control strategies for the turbine, and a detailed study of the controller and feedback loop would be beneficial.

On the other hand, Hofer et al. [57] used the ATHLET thermal–hydraulic algorithm to study the control strategies of a sCO_2 Decay Heat Removal System (sCO_2-DHRS) during unexpected failures. In situations like long-term station blackouts and ultimate heat sink loss, the system, coupled with a Konvoi PWR of 3840 MW thermal power, adopts conservative boundary conditions. Moreover, the fan speed controlled the Compressor Inlet Temperature (CIT), the turbomachinery shaft speed controlled the TIT, and the valve controlled the H_2O side Compact Heat Exchangers (CHX) outlet temperature. The existing sCO_2-DHRS architecture can manage some faults, while others require immediate intervention or design modifications. An inventory control system or cycle shutdown can reduce the pressure resulting from gas cooler fan failure. Additionally, an unplanned fan speed-up could cause a compressor surge or cycle pressure drop into two phases. The study stresses how important it is to use advanced control strategies to reduce thermal stresses and make sure that failure scenarios are handled effectively. It also stresses the need for backup cycles and better modelling of turbomachinery, especially at low speeds and when two-phase inlet conditions are present. Future investigations should focus on the feasibility of system restarts and detailed thermal stress analysis.

The development of control strategies for RC-SCBC is challenging due to the extremely nonlinear features near the supercritical zone of the cycle. To prevent oscillations that degrade equipment and cycle performance, the control system must respond quickly and precisely to power load needs. Due to the significant connection between cycle net load and the main MCIT, feedback loops cause instability. Traditional, manually tuned PID controllers may not be enough for quick ramps.

To address these challenges in a 10 MW_e system, Albrighta et al. [58] used advanced control algorithms to handle these problems. The cascaded inventory management control (IMC) with pressure control reduces response times by directing system pressure towards the load control output, but it also increases MCIT-load interactions, necessitating alternative control mechanisms. Gain scheduling stabilises Cooler Outlet Temperature (COT) changes by managing cooling water flow. The primary compressor Inlet Guide Vane (IGV) control eliminates oscillations and adapts to rapid temperature changes via feed-forward control. The sCO_2 bypass flow control method separates MCIT from net load, which stops oscillations and lets precise load tracking happen at a small cost to efficiency. Both approaches are vulnerable to sensor noise, although first-order filtering improves stability. The authors proposed that a future study will use enhanced predictive control to improve cycle efficiency and settling time.

In contrast, Gao et al. [59] proposed a preliminary design system and safety analysis methodology for a direct-cooled reactor system (SCFR-300) with an SRC-SCBC to generate electricity. The net power of the system was 63.9 MW_e. This study used different control strategies to ensure the sCO_2-cooled reactor system's normal and safe functioning during start-up, shutdown, and part-load transients. The TIT is controlled by the reactor control rod during start-up and part-load operations. The shaft speed (N) is controlled by the TBV, and the CIT is controlled by the BCV. In part-load operations, inventory control strategy used to control compressor volumetric flow rate ($\dot{V}_{Com}$) by adjusting the R-CV and compressor THV to prevent surge or choke, and in addition, TBV and turbine control valve schemes are used to protect turbine overspeed and reactor and compressor overflow. All of these control strategies used PID controller which improved cycle efficiency and stability. Controlling pressure and temperature ensures system integrity, while flow management enhances heat transfer efficiency, increasing component lifespan and lowering maintenance costs. Further research should focus on implementing these control strategies through both experimental and numerical methods under diverse conditions. Illustrating the feedback loops with controllers and integrating advanced control strategies would be beneficial avenues for future investigation.

Addressing start up control strategy in more compact system, Hexemer et al. [44] develop a transient model for a 100 KW_e SR-RC-SCBC. The main compressor operates at an idle speed once it meets the specified parameters, which include a TIT of 65.6 °C, main compressor inlet conditions of 37.8 °C, and a pressure of 8.62 MPa. This idle speed ensures a sufficient surge margin and a high-pressure ratio. The recompressor is kept separate during the early phase in order to provide an adequate flow of CO_2 for the main compressor. The primary compressor speed is increased from 37,500 to 42,000 rpm before powering the recompressor to idle speed in order to achieve the desired pressure ratio balance. The collaboration of control valves, which includes two R-CV as well as inlet and output isolation valves, enables the recompressor to be connected quickly and securely. Furthermore, the recompressor automatic speed setpoint is utilised to control the recompression pressure ratio in accordance with the main compressor pressure ratio via the PI controller. This study presents a fundamental framework for implementing efficient control strategies in recompression Brayton cycles, highlighting the significance of dynamic, real-time control modifications to uphold system stability and efficiency.

In contrast, Clementoni et al. [43] used the previous transient model for three different control strategies. The control strategies include direct shaft speed control, which adjusts turbine-compressor speed to vary system power. Second, thermal–hydraulic cycle control regulates turbine-generator speed through motor-generator load adjustments and modulation of the compressor recirculation valve. Finally, PI controllers maintain turbine and compressor inlet temperatures for efficient and reliable operation. The thermal–hydraulic cycle control response was extremely similar to the setpoints for these parameters, despite large oscillations in compressor recirculation valve position caused by controlling with PI constants that were developed using stable modelling assumptions and not optimised for actual system operation. Tuning compressor recirculation valve PI constants for turbine-compressor speed control should reduce valve position oscillations and stabilise system responsiveness. However, adjusting PI constants may reduce load setpoint responsiveness. This study emphasizes the complex balance between stability and responsiveness in control systems, as well as the need for continuous PI improvement and real-world testing to achieve optimal performance.

Lastly, Du et al. [60] conducted an extensive numerical analysis of four control strategies for a transient model for a 1 MW_e RC-DRC-SCBC-cooled reactor system. These control strategies included an inventory control strategy to control the MCIP, a water cooler control strategy to control the MCIT, an output power control strategy via reactor power changes, and a circular flow control strategy that included two control loops. One controls coolant flow rate by altering compressor speed using a variable-frequency motor, and the other controls reactor outlet temperature. PID controllers were employed for all control strategies, and the load in the transient model was varied from 100 % to 40 %. All control strategies work well with the control variable's design value. Under low load, continuous flow operation with a lower reactor temperature reduces cycle performance. Meanwhile, with a constant reactor outlet temperature operation plan, system parameters vary substantially, resulting in a longer transition time. Therefore, the compressor operation line included an improved circular flow control system to avoid a surge or chock. Optimised operation provides the benefits of both control strategies. During the transient stage, the optimised control scheme makes the sCO_2-cooled reactor system efficient and rapidly responsive. This study lacks experimental validation and advanced optimisation strategies. Additional research should incorporate experimental validation and enhanced control methods to improve resilience and efficiency.

Based on the aforementioned studies, it is essential to highlight a sometimes neglected yet crucial difference from a control standpoint: the disparity between cold-start and hot-start strategies. Cold start indicates the commencement of the cycle from ambient or subcritical conditions, necessitating incremental CO_2 pressurisation and heating through the pseudo-critical phase. This requires more stringent control of heater ramp-up, inventory loading, and compressor surge mitigation, specifically because of the nonlinear thermophysical characteristics near the critical point. In contrast, hot-start (or warm-start) scenarios begin with the system in a moderately heated and pressurised condition, often due to a warm shutdown. These restarts generally avoid the intricate phase transition and concentrate on reinstating stable flows and turbomachinery velocities. The reviewed studies, including those by Conboy et al. [54] and Liese et al. [34], illustrate significant disparities in both methodology and control rationale. Identifying and clearly addressing these varying control requirements is crucial for formulating effective startup strategies in practical sCO_2 systems.

3.2. Off-design performance dynamic models

Gao et al. [61] developed a part-load SR-SCBC direct-cooled reactor control strategies. The strategy included CIT control utilising an air-cooling control strategy, generator power control utilising a turbine bypass control strategy, compressor-choking control utilising a throttle valve control strategy, and reactor power control using a passive power control method. Additionally, PI used as the controller for both the bypass and air-cooling strategies. After a detailed comparison of three bypass layouts, the upper-cycle bypass valve was selected as the best layout for the system. It is highlighted that system stability increases when the bypass valve is slightly open during the full load condition, with little influence on cycle efficiency. Future studies will refine the throttle valve control strategy's closed-loop control system. This work provides a comprehensive framework for increasing the control flexibility and stability of sCO_2 direct-cooled reactors. However, the findings from this study need to be validated through an experimental analysis and try to use a combined control strategy and advanced algorithm to enhance the system's efficiency and response.

Similarly, Milani et al. [62] proposed a 10 MW_e solar-assisted RC-DRC-SCBC situated in Port Headland, Northwest Australia. The inventory tank regulates the TIT, enabling load adjustment through the functional correlation between TIT and the power grid. The authors conclude that inventory control is most appropriate for power decreases that are both significant and stable, as the process has a long-term constant and is temporarily disrupted by the withdrawal or addition of CO_2.

By contrast, Du et al. [63] studied the impact of a turbine equipped with Variable Inlet Guide Vanes (VIGV) for 1D design and off-design models on a similar recompression cycle. It was found that use of a Variable Inlet Guide Vanes (VIGV)-equipped turbine improves the efficiency of the system and turbine by 1.34 % and 2.86 %, respectively, at a load of 10 %. However, the mass flow rate and pressure ratio of the inventory-controlled system decreases by 5.46 kg/s and increases by 0.023, respectively, which further reduces the surge margin of the two compressors, thus limiting the nozzle opening of the turbine. Moreover, it was found that using hybrid strategy that combines inventory control and turbine bypass control enhances the use of the VIGV-equipped turbine and increase cycle efficiency and decrease the compressor surge also. This study needs to be test with different control strategies under low load condition in order to figure out which strategy is most efficient for the study.

Heifetz et al. [64] adopted a different approach by examined the load-following capabilities of RC-DRC-SCBC and using PI controller. It was found that the turbine bypass valve controller reacts promptly to adjust to the load requirements, but efficiency decreases during steady-state operation, but the stability of cycle need to be examined under a conditions of measuring sensor time delays.

Regarding the load following performance, Tom et al. [65] designed an IMC for a 10 MW_e RC-SCBC for sCO_2 pilot plant facility on SwRI's campus in San Antonio. The IMC can support system fill, inventory control during load transitions, pressure and mass control of the power block, and provide auxiliary supply flows. In the event of an emergency, the IMC can provide the Dry Gas Seals (DGS) supply flow via the DGS boosters and/or passive backup from the inventory storage tank and fill system. System component specifications are affected by the planned operating cases, volume in the RCBC cycle, IMS requirements and overall cost. However, this control strategy needs to be test experimentally, as it may be not efficient enough. Also, the Typical sizes of bulk liquid tanks are 14, 30, and 50-ton tanks holding 12,700, 27,000, and 45,000 kg, respectively.

Li et al. [66] conducted a comprehensive computational study for sCO_2 power cycle with WHR heat source from a partial gas turbine. The research study explicitly investigated the impact of fluctuating external factors, including ambient temperature, flue gas inlet temperature, and flue gas mass flow rate. Cycle maximum pressure, minimum pressure, and SR were key control elements in the study. An inventory control approach monitored CO_2 mass flow; a valve regulated SR in the cycle. Utilising multi-objective optimisation, the initial design achieved significant objectives, including a net power production of 8.67 MW_e and an exergy efficiency of 54.76 %. The net power production increases by 0.62 MW_e for every 5 kg/s increase in flue gas mass flow rate and 0.29 MW_e for every 10 °C increase in input temperature. Nevertheless, the exergy efficiency exhibits an initial increase followed by a subsequent reduction with the increase in flue gas mass flow rate. Both the net power output and exergy efficiency decrease as the ambient temperature increases. To summarize, the control of the highest pressure in the cycle is vital to adapt to fluctuations in flue gas characteristics, while modifications to the lowest pressure in the cycle are necessary to accommodate shifts in ambient temperature.

Correspondingly, Park et al. [67] conducted a study that examined the operation and control strategies of a sCO_2 recompression cycle using the sCO_2 Integral Experimental Loop (SCIEL) facility. The efficiency and power generating abilities of the SCIEL system were tested through experiments and Multi-dimensional Analysis of Reactor Safety (MARS) code simulations. The SCIEL system was found to produce between 1.1 kW_e and 1.3 kW_e. The simulations and experimental data showed a reasonable level of consistency, while there were minor differences seen near the compressor output. These differences were attributed to uncertainties in the measurements and errors in the homologous curve. The significance of valve control in managing cycle operations was exemplified by successfully reducing power output to 50 % of steady-state levels without making any modifications to the heat source, heat sink, or turbomachinery speed. Thus, the utilisation of bypass valve control was determined to be a highly successful approach for regulating cycle power. It was proposed that expanding the MARS code, which was initially created for water reactor systems, could improve comprehension and advancement of control strategies for the sCO_2 Brayton cycle. Although a solid basis for controlling the sCO_2 Brayton cycle was established, the necessity for continuous improvement and verification was emphasised.

Furthermore, Oh et al. [68] investigated control strategies for an Electric Thermal Energy Storage (ETES) system integrated with sCO_2 recompression cycle to optimise performance and stability under part-load operation and fast power shifts. This study used HTR bypass control to control CO_2 flow when TIT is low, inventory control to reduce heat load for break-even and control MCIP, and PID controllers to manipulate mass flowrate for the cooler to control MCIT. When using inventory control, the surge margin exhibits a consistent trend, as opposed to the fixed complete inventory case. Also, inventory control system transient analysis for operations that raise power from 0 % to 100 % can lower changes in physical parameters that are caused by fast property changes in situations with pseudocritical pressure. It is recommended that these control strategies be employed in CSP or advanced nuclear power plants, as they enable the ETES-sCO_2 cycle to operate efficiently under a variety of conditions, ensuring a rapid and stable power ramp-up. Furthermore, it is imperative to evaluate these control strategies during the startup and shutdown phases to gain a comprehensive understanding of their effectiveness and robustness in all operational states. This will also be beneficial to incorporate a feedback control loop for inventory and HTR bypass control strategies, as well as combined control strategies.

Tang et al. [69] conducted a study to assess the transient turndown response of various control systems for a simple cycle that was heated by air and cooled by water. The study also involved the use of IGV to control the compressor. The study demonstrated that implementing inventory control leads to maximum cycle efficiency, while turbine throttle control allows for faster turndown. The study by Alfani et al. [70] examined how various inventory control strategies affect the steady-state off-design performance of a recompression cycle. The cycle was heated by salt and had set turbine intake and compressor inlet temperatures. The researchers discovered that decreasing the pressure at the compressor inlet as the load falls enhances the cycle's efficiency compared to a scenario with a fixed inlet pressure. Additionally, it was observed that maintaining the salt cold temperature at the design value decreases efficiency compared to allowing the temperature to rise during part-load operation.

In this study, Duniam and Veeraragavan [71] examined the steady-state off-design performance of a recompression cycle. It investigated how this performance varied with varying ambient temperatures and salt mass flow rates. The cycle was cooled by a natural-draft dry-cooling tower and heated by a two-tank sensible storage system. The model establishes a fixed compressor intake pressure and turbine inlet temperature, assumes variable-speed compressors, and uses inventory control to regulate the cycle mass flow rate, thereby controlling power output. The results show that the cycle can sustain the desired power output at high ambient temperatures by allowing both the shaft speed and turbine inlet pressure to exceed the design limits. It concluded that higher ambient temperatures at the design point are advantageous for enhancing the capacity during the hottest seasons of the year. Yang et al. [72] examined the stable off-design efficiency of a basic cycle combined with a solar power tower equipped with a two-tank storage system. This model controls the cycle power output by manipulating the turbine intake pressure, as well as the compressor inlet temperature, turbine inlet temperature, and compressor inlet pressure. The results demonstrated that the temperature of the salt exiting the cycle fluctuated depending on the load, which subsequently impacted the receiver's efficiency.

Yang et al. [73] carried out a comparative analysis of the steady-state off-design performance of various cycles (simple, reheating, recompression, and intercooling) heated by salt. The study assumed fixed turbine intake and compressor inlet temperatures. The model employs inventory control and variable-speed compressors to maximise cycle efficiency for a specific load. The findings demonstrate that the intercooling and recompression cycles maintain their superior efficiency compared to the simple and reheating cycles throughout periods of reduced workload. This approach is consistent with findings from Li et al. [74] who conducted a comparison between inventory control, turbine bypass control, and turbine inlet temperature control in a simple cycle heated by a lead-cooled fast reactor. The study assumed that there was a fixed compressor inlet temperature and a variable compressor speed. The results indicate that implementing inventory control leads to the greatest cycle efficiency when operating at less than full capacity.

T. Neises [75] contributed further by developing an off-design cycle convergence and optimization model for CSP systems to optimize main compressor inlet pressure and temperature. This model incorporates actual restrictions, including air-cooler fan power, compressor working range, high-side pressure, and Heat-Transfer Fluid (HTF) outlet temperature, to better reflect optimal off-design behaviour than less constrained models. High ambient temperatures cause the cycle's pressure limit to reach before the design HTF outlet temperature, which in turn reduces heat input and net power output, leading to operational issues such as solar receiver and Thermal Energy Storage (TES) system overheating. At low ambient temperatures, the model reduces air-cooler fan power to maintain compressor inlet temperatures and meet the design HTF outlet temperature, eliminating surges. The study demonstrates that variable IGVs or variable-speed turbocom-pressors may increase performance in colder and part-load conditions by optimizing compressor shaft speeds. Although future research should examine the trade-offs and practicalities of operating compressors at greater than design shaft speeds, it finds that compressor shaft-speed control benefits warmer climate CSP systems. To maximise CSP system technoeconomic performance, turbomachinery models and cycle design-point optimisation should be studied.

Elaborating on the impact of compressor inlet temperature and load adaptations, Dyreby [26] found that cycles designed for a compressor inlet temperature close to the critical point cannot sustain the desired power output when the compressor inlet temperature rises without exceeding the designated high-side pressure. Floyd et al. [76] used this finding in their transient Plant Dynamics Code to investigate how lower water temperatures impact the steady-state off-design performance of a recompression cycle connected to a sodium-cooled fast reactor while assuming a constant CO_2 inventory. It was discovered that when the temperature at the inlet of the compressor exceeded the intended level, the cycle without any active control had a decline in heat input and power output. However, the main-compressor speed control cycle was able to maintain the desired heat input at the design point.

Bennett et al. [77] examined the off-design performance of a recompression cycle with reheat, focusing on the steady-state conditions and maintaining fixed temperatures at the turbine inlet and compressor inlet. The system employed IGV manipulation on the initial stage of every compressor and inventory control to enhance cycle efficiency. The data demonstrates that the selection of the design-point compressor intake temperature should be influenced by the anticipated off-design compressor inlet temperature. Avadhanula and Held [78] conducted a comparison between the transient-cycle model and operational data for a basic cycle that was heated by exhaust gas and cooled with water. The comparison included inventory control and a variable-speed turbocompressor. It demonstrated that the system's response is very sensitive to turbocom-pressor control, necessitating a thorough understanding of the subject.

De la Calle et al. [79] investigated further off-design performance of a molten salt-heated, air-cooled recompression cycle. Moreover, a variable-speed recompressor to optimise efficiency and inventory control was used, aiming to attain desired conditions at the outlet of the low-temperature recuperator. The researchers examined three distinct plant sites and discovered that each site had a distinct optimal design-point compressor inlet temperature. Battisti et al. [80] investigated the transient behaviour of a water-cooled simple cycle that was heated by Therminol VP1 from a constant-temperature baseline source and a variable-temperature solar field. It utilised inventory control to maintain constant low-side and high-side pressures. It was discovered that systems using a solar field with varying temperatures may not achieve a state of equilibrium. Reznicek [81] examined the stable off-design efficiency of a recompression cycle that is heated by salt. The purpose was to evaluate the efficacy of regenerators and counterflow heat exchangers in the recuperation process. The model was employed to set the compressor inlet temperature and utilise inventory control, salt flow rate, main compressor IGV, and recompressor IGV to attain the desired power output, design turbine outlet temperature, design main compressor inlet pressure, and design recompression fraction. The findings indicated that cycles utilizing regenerators exhibit little oscillation but can attain comparable part-load performance to cycles employing counterflow heat exchangers.

In this study, Dyreby et al. [82] controlled various parameters, including the recompression fraction, main compressor shaft speed, and low-side pressure of the recompression cycle. The objective was to maximise steady-state off-design efficiency at varied power outputs while assuming fixed turbine and compressor inlet temperatures. The results showed that reducing the low-side pressure while decreasing the temperature at the compressor inlet can enhance the cycle's efficiency compared to retaining the pressure at the design point. Sleiti and Al-Ammari [83] employed Dyreby's [82] control strategy to integrate a 50 MW_e dry precooler-intercooled sCO_2 power cycle with a solar power tower (SPT) and direct oxy-combustion (DOC). The results showed a strong correlation with Dyreby's findings. The pressure-sliding control strategy was implemented to align the power output with the demand.

However, it has been determined that more improvements are necessary to reduce the decrease in efficiency when the system is operating below its maximum design capacity. Therefore, it is advisable for future studies to investigate advanced control strategies for these configurations in order to improve performance in response to changing load situations.

Lastly, Li et al. [84] utilised separation control and inventory control strategies to optimise the net power output of a sCO_2 power system, which is powered by the waste heat from the exhaust gas of the gas turbine system. During the off-design operation stage of the system, the maximum net power exhibits a nearly linear increase, ranging from 1581 kW_e to 2924 kW_e. However, the maximum attainable net power output consistently decreased as the temperature and mass flow rate of the exhaust gas increased due to the impact of separation control. Although the inventory control system needed more time to adapt and optimise its performance, it often produced higher net power output under off-design situations compared to separation control.

Table 1 shows a brief summary of key research papers. This table includes details such as the power output and layout of the cycle, the heat source used, the kind of controller, the control parameters, the control strategy used, the dynamic model utilised, and whether the study was conducted experimentally or numerically. As noted, that there is only one experimentally study that conducted an experimental control strategy investigation for 300 KW_e RC-DRC-SCBC with oil fired boiler during the start-up operation [52]. In addition, the power output varies significantly across the cycles, ranging from 0.05 MW_e to 133.09 MW_e, indicating a broad range of heating sources for small and large scale and it can be noted that for the large power cycle that the preferrable heat source it could be a nuclear application or coal fired applications with specific solvent in order to produce high thermal power [85].

3.3. Summary

According to the studies above, it is obvious there are various control strategies available for managing the load, and each strategy has its own set of positive and negative aspects. Table 2 provides a summary of the primary features associated with various control mechanisms. In fact, every type of control strategy is a combined approach. For instance, the inventory control strategy is used to control the load through regulating the TIT using particular strategies like regulating compressor speed, utilising various valves, and managing the heat source. However, while this strategy is steady, it has its constraints. The inventory control strategy is slow to respond and works well only within a small power adjustment range (112.5 %–50.6 % of the rated power), but it can keep the cycle efficiency steady.

In contrast, using the bypass valve control strategy will decrease the cycle efficiency and increase the thermal stress on the heat exchanger, but it is suitable for wide range adjustment (100 %–30 % of rated power) and has a faster response [86]. Similarly, in alternative load following

Table 1
Summary of the basic control strategy for SCBC.

Cycle	Power [MW_e]	Heat source	Controller type	Control parameters	Control strategy	Dynamic model	Exp./Num.	Ref.
SR-SCBC	0.05	WHR	PI	- TIT	- INV	Startup Shutdown Heat Load	Numerical	[51]
RC-DRC-SCBC	10	Comb	PI	- MCIT - SCBC-P - CS - TIT/ EGT - AFR	- BCV - INV - R-CV - F-CV - EGT-SP	Startup Shutdown Load Following	Numerical	[34]
RC-DRC-SCBC	10	CSP	N/A	- TIT	- INV	Load Following	Numerical	[62]
SR-RC-SCBC	5	WHR	PID	- TIT - MCIP - MCIT	- TBV - THV - BCV	Changing WHR Conditions	Numerical	[41]
RC-DRC-SCBC	0.3	OFB	PID	- MCIT - TIT - TF - MCIP	- BCV - TBV - TAC-TH - TAC-SP - INV	Startup	Experimental	[52]
RC-DRC-SCBC	2	CSP/ AFB	PI	- MCIT - TIT - PB - SR	- BCV - HS - THV - INV	Startup	Numerical	[55]
SR-RC-SCBC + Power Turbine	1	Electrical heater	N/A	- MCIP - MCIT - MCOP - TIT - $\mathbf{P_{output}}$	- Pre - BCV - THV - HS - TBV	Startup	Numerical	[56]
SRC-SCBC	63.9	SCFR-300	PID	- TIT - **N** - CIT - $\dot{\mathbf{V}}_{\mathbf{Com}}$ - CS - Overspeed - Overflow	- HS - TBV - BCV - INV - THV	Startup Shutdown Part-Load	Numerical	[59]
SR - RC-SCBC	133.1	SM-PWR	PID	- **N** - TIT - MCIT - $\dot{\mathbf{m}}_{\mathbf{sCO_2,MC}}$ - MCOP - RCOP	- TBV - CP - BCV - FS - THV	Load Following	Numerical	[85]

Table 2
Features for various control strategies.

Control strategy	Work principle	Pros	Cons
Inventory	Control the cycle pressures through withdrawals or additions of CO_2 mass flowrate to adjust the load.	- Increase cycle efficiency	- Slow response
			- High design cost - Narrow range for load change - Leakage risk
Turbomachinery speed	Change the working fluid mass flowrate through changing the turbomachinery speed.	- Fast load change	- Not suitable for coaxial cycle and large sCO_2 power cycle
Valve	It may be bypass or throttling valve used to change mass flowrate or pressure.	- Quick response	- decrease cycle efficiency
		- Flexible operation - Affordable	- Narrow range for load change - Potential pressure drops - Reliability Issues
Heat source	Changing the heat input.	- Increase cycle efficiency - Flexible operation - Safe operation	- Slow repones - Reliability Issues

control schemes, the TIT must be controlled using different approaches. Simultaneously, certain literature suggests adjusting the split ratio in compression SCBC through the use of valves or by altering the speed of the compressor in order to enhance the efficiency of the system. The presence of numerous controlled variables and combination modes, which will be discussed in detail in the next section, might have an impact on the power-level and efficiency of the SCBC. Consequently, it is currently challenging to identify the most efficient load following approach during the entire operating process.

4. Combined control strategies

Combining different control strategies can enhance the system's efficiency, but the complexity of the control strategy will increase the difficulty of controlling the system. Oh et al. [87] studied the control strategy of a directly cooled nuclear reactor Brayton cycle for a load step drop from 100 % to 0 %. The findings indicated that combining core bypass control with inventory control can fulfil the load requirements and achieve high cycle efficiency.

Extending this control strategy concept, Chang et al. [88] investigated the performance of five control strategies for an 8 MW_e RC-DRC-SCBC under off-design working conditions, namely inventory control, turbine bypass control, Compressor Back-Flow (BFV) control, TIT control, and Turbine Inlet Pressure (TIP) control. The single control method decreases system output power, fluid machinery efficiency, and thermal efficiency. The hybrid control strategy (compressor back-flow control and inventory control) improves operating efficiency, prevents choking, and enhances turbine efficiency by 4.5 % and system thermal efficiency by 7.1 % compared to the inventory control method. Although the integration of control techniques clearly improves the system's efficiency, adopting this hybrid strategy in real-world scenarios can be challenging due to the heightened complexity of coordinating numerous control mechanisms simultaneously.

Wang et al. [89] explored different control strategies for a 446.7 KW_e RC-DRC-SCBC using a heat source from burning white oil at temperatures up to 2067.15 K. The aim was to optimise the efficiency of the cycle at the kW_e-level. A test was conducted on inventory control, valve control, and a combination of inventory and anti-surge control, utilising PI or PID controllers. Research has revealed that relying alone on inventory control is restricted by compressor surge at low loads. However, when inventory control is combined with a compressor return valve, surge is prevented and load needs between 0–100 % are successfully met. The integration of inventory control with the HTR bypass valve was found to end up in a slower operational speed. In general, it was discovered that coupled control strategies were more effective than valve controls throughout the entire range of loads. The importance of including different control strategies for low-load conditions was emphasised, and it was recommended that future study should concentrate on coordinating controllers and examining start-up and shutdown procedures. Nevertheless, it was observed that further investigation into advanced control methods and empirical verification in practical scenarios is necessary to enhance the credibility of the results.

In addition to implementing and evaluating the combined strategies. Wang et al. [89] proposed valuable insight in the trade-off between stability, efficiency, and response. The study showed that using the inventory control strategy will enhance the cycle efficiency, but it suffers from instability and slow response at low loads due to possible compressor surge. In contrast, combining the inventory control strategy with return valves enables safe operations over a full load range, but the control structure becomes more complex. The dynamic system is affected by the combined control strategy; for instance, the result for HTR with the inventory control strategy shows slower stabilisation, and the difference is due to the fluid transport delay, highlighting the potential interface between surge control and the heat recovery function. The aforementioned observation highlights the importance of carefully regulating the dynamic interactions between the control loops and underlines the need for a coordinated control scheme in multi-loop sCO_2 power cycles.

In contrast, Zhaozhi et al. [90] analysed three configurations of SCBC—SRC, PC, and RC—integrated with nuclear reactor cooling systems to produce mechanical or electrical power for marine propulsion. Four strategies for control were evaluated for load-following operation. In electric propulsion systems, Strategy I integrated inventory control with compressor speed regulation to sustain a steady turbine speed and optimise thermal efficiency, although it was constrained to a load range of 70–100 % due to surge risk. Strategy II utilised a turbine bypass and throttle valve to provide a broader load range of 10–100 %, but this resulted in higher exergy losses. In mechanical propulsion, Strategy III employed variable compressor speed alongside turbine speed control, providing full load flexibility and optimal efficiency. Strategy IV implemented a turbine bypass with a constant compressor speed for pressure adjustment. The study emphasised a significant trade-off between thermal efficiency and control flexibility, with Strategy III identified as the most balanced in performance and adaptability.

Zhou et al. [91] examined four hybrid control approaches for a 4 MW_e lead-cooled fast reactor (LFR) sCO_2 power cycle. The system's load was controlled, and efficiency improved using Rotational Speed-Inventory (RS-INV), Turbine Inlet Pressure (RS-TIP), Bypass (RS-BYP), and Turbine Inlet Temperature (RS-TIT). Each technique used different characteristics to regulate demand for power. Everyone used the RS control method to change the compressor or turbine rotational speed to change CO_2 mass flow rate and pressure. The RS-INV strategy adjusted CO_2 mass flow to match output power. But the RS-TIP strategy used a relief valve to modify the turbine's input pressure, which changed mass flow by changing expansion and compression ratios. RS-BYP changed turbine mass flow rate bypass valve by changing rotation speed. By varying lead–bismuth eutectic (LBE) and water mass flow rates, RS-TIT altered TIT. The RS-TIP and RS-BYP strategies improved thermal performance and safety. RS-INV was most efficient for loads from 33 % to

108 %, whereas RS-TIP was best for 0 % to 108 %. Power capacity was limited to 17 %–108 % by RS-TIT. Further study will focus on advanced algorithm-based design optimisation and dynamic performance evaluations of the LFR-sCO_2 system.

Furthermore, Gini et al. [92] developed three-control strategies for a 1.6 MW_e SR-SCBC that utilised Molten Salts (MS) for heat supply. The objective of this study was to propose an appropriate control strategy that ensures efficient and safe operation, during the part load operating. The initial control strategy involved a combined approach, which utilised the change of shaft speed (N) and sCO_2 mass flowrate ($\dot{m}_{co_2}$) for controlling power (P). Additionally, the TIT was controlled by manipulating the MS mass flowrate ($\dot{m}_{MS}$), while the CIP was controlled by inventory control strategy. The results indicate that by optimising the combination of N, MS mass flow, and CO_2 loop mass, the efficiency may be maximised, ensuring that the compressor inlet conditions remain practically constant (33 °C, 83 bar) up to 51 % part-load. The TIT which is near the specified value of 565 °C, along with the excellent efficiency of the turbomachinery at part load, enables a decrease in efficiency of around 20 % compared to the efficiency at the design point. Future work will focus on studying the creation of control strategies during transients. The aim is to optimise the load response time, minimise the influence on system components, and prevent dangerous operating conditions.

Ding et al. [93] adopted a comparable approach, comparing different control strategies for the transient model of the 10 MW_e recompression sCO_2 Brayton cycle (including combined and single control strategies). The main control parameters were MCIP and TIT in the transient simulation when the thermal load for the heat source or reactor changed. Furthermore, the individual control strategies included TBV, Turbine and Heater Bypass (THBV), BCV, THV, inventory, and the shaft speed. On the other hand, the combined control strategies were TBV with a BCV and TBV with a THV. The results show that shaft speed control had the maximum efficiency, and BCV control had the highest turbine shaft power, from 100 % to 80 % thermal power. When MCIP was controlled using the BCV and THV, the pressure dropped below the critical value, while inventory control increased the pressure fluctuation. Therefore, the most effective approach in this study involved utilizing a combination of control strategies. Specifically, combining the turbine bypass with the BCV control strategy resulted in reduced pressure fluctuations, while both strategies successfully raised the pressure above the critical value. This study provides optimal control strategies for SCBC performance and stability under different thermal loads. However, further research is necessary to ascertain the startup and shutdown efficiency of this control strategy.

Table 3 provides an overview of the Kay studies that used combined control strategies for the sCO_2 power cycle. Note that all the studies were numerical and did not test these control strategies during start-up, shutdown, or emergency situations. Therefore, the following table indicates that further research is necessary to understand the effect of the combined control strategies on transient behaviour, and these strategies need to undergo experimental testing to enhance their reliability.

5. Advanced control strategies for sCO_2 power cycles

This section reviews previous studies that used advanced control strategies alongside combination or basic control strategies. The advanced control strategies in this section include ESC, Iterative Learning Control (ILC), dual PID, Predictive Control Model (PCM), and ANN.

Minh et al. [94] presented a dynamic model for a 2MW_e solar-assisted RC-DRC-SCBC, which utilized an inventory control technique to control the TIT in order to effectively monitor the load. This monitoring was conducted by analysing the functional correlation between TIT and the load on the system. A PI controller was utilized, utilizing two operational configurations: Flexible Temperature Mode (FTM) and Constant Temperature Mode (CTM). In the CTM, the reference TIT was kept constant at 600 °C, whereas in the FTM, the TIT changed in accordance with fluctuations in solar thermal power. Both CTM and FTM were found to significantly increase the total energy output, with gains of up to 37.1 % on specific test days, when compared to a conventional method. However, it is necessary to do additional research to examine the scalability and durability of these control techniques, particularly in situations involving severe weather or sudden fluctuations in solar input. This is important to confirm their usefulness in a wider range of operating scenarios.

Similarly, Hu and wang [95] studied different control strategies for a 200 kW_e SR-SCBC-CSP integrated system to improve power generation efficiency. Moreover, the real-time adjustment of turbine inlet parameters is achieved by PID control to improve efficient and stable output power of the system. Consequently, the average daily generating capacity of the system is 2.06 % higher when the ESC strategy is applied, and 2.15 % higher when the ILC strategy is applied. Overall, these results compare favourably to the traditional fixed inventory control strategy.

Table 3
Summary of the combined control strategies for SCBC.

Cycle	Power [MW_e]	Heat source	Controller type	Control parameters	Control strategy	Dynamic model	Exp./Num.	Ref.
RC-DRC-SCBC	8	N/A	N/A	- MCOP - TIP - $\dot{m}_{BF}$ - $\dot{m}_{HS}$ - TIT	- INV - BFV - TBV - TIP-BYP - HS - INV + CBF	Off-Design (Load Fluctuation)	Numerical	[88]
Coaxial-SR-SCBC Spilt shaft-SR-SCBC	4	LFR	N/A	- $\dot{m}_{co_2}$ - TIP - BYP Ratio - TIT	- RS-INV - RS-TIP - RS-BYP - RS-TIT	Off Design (Load Fluctuation)	Numerical	[91]
SR-SCBC	1.6	MS	N/A	- P - TIT - CIP	- $N_{sh}+\dot{m}_{co_2}$ - $\dot{m}_{MS}$ - **INV**	part-load	Numerical	[92]
RC-SCBC	10	Reactor	N/A	- TIT - MCIP	- INV - TBV - THV - BCV - THBV - N_{sh} - TBV + BCV - TBV + THV	Thermal load changing	Numerical	[93]

Furthermore, Li et al. [96] also proposed a comparative analysis between fixed inventory control and an Extremum-Seeking (ES) feedback controller for regulating TIT to improve the net power output in a SR-SCBC. The power cycle is heated directly using parabolic troughs and has a net power production of 1 MW_e. In addition, a basic PID controller was used to ensure that the compressor inlet conditions remain in a fully critical state during the winter. According to the results, the suggested ES algorithm worked just as well as or better than the fixed inventory method, and it required a lot less work to calibrate. The ES algorithm proved to be effective, even though fixed inventory control may require adjustments to account for temporary seasonal fluctuations in the harsh conditions under evaluation. Still, it's important to remember that testing the ES algorithm's implementation using a transient model of the cycle is also necessary to include the start-up and shutdown phases for a full evaluation.

Wang et al. [97] adopted more extensive approach, improving two Coordinated Control Systems (CCS) to enhance performance during the rapid load change in a 300 MW Coal-Fired Power Plant (CFPP) with a sCO_2 cycle and Energy Storage (molten salt). Both CCS utilized PID controllers, which had two outputs: electric power output (P) and main steam pressure (P_{ms}), and four inputs: coal flow (μ_{CF}), turbine governor valve opening (μ_{TG}), heat-conducting salt flow (G_{hot}), and extraction steam flow (G_{ES}). The turbine-follow mode was adopted in this study. In the first CCS, the μ_{CF} used to regulate P and the μ_{TG} used to control P_{ms}. The combination of Two other inputs with μ_{CF} influence system load: G_{ES} with μ_{CF} reduces system load, and G_{hot} with μ_{CF} raises it. Switching controllers between these two combinations enables the changes in system load. In the second CCS, in this CCS a Dual Control Strategy (DCS) is used and the G_{hot} and G_{ES} were used as primary controls, while μ_{CF} was the secondary control. Results indicate that the second CCS responds faster than the first and standard CCS. In addition, the second scheme had the lowest Integral of the Absolute Error (IAE) and Time Square Error (ITSE) indices. Automatic generation control (AGC) performance indicators were 9.03 and 8.76 during load increases and decreases, respectively. These findings imply that the second CCS is the best. To confirm its practicality, an economic analysis and startup and shutdown tests are required.

In addition, Wang et al. [98] implemented the same control loops for TIT, MCIT, and compressor surge margin as those in [89] within the same sCO_2 cycle, achieving a power output of 370.1 kW_e and a cycle efficiency of 26.5 %. The study focused on optimizing the system SR and evaluating its effect on various control strategies, and for accurate control system a Gain-Scheduled PID (GS-PID) controller used for inventory and TAC control strategies, while single PI or PID controllers were used for other loops. This study conducted a comparison between inventory control with SR control and TAC control with SR control, revealing that inventory control with SR control enhanced cycle efficiency during load changes from 100 % to 20 %. Below 20 % load, cutting off the RC loop by closing throttle valves proved more efficient, eliminating the need for SR control. An ANN was used to analyse SR, revealing that optimal SR is influenced by low and high recuperator effectiveness, minimum pressure, and maximum pressure. The ANN model, with 300 hidden layers, was trained on 30 design sets. The results showed that the compressor is prone to surge at low loads, and surge prevention measures impact the SR's optimal trend. Additionally, employing flow merge point control can enhance system efficiency without needing SR optimisation.

Earlier, a study conducted through researchers in Argonne National Laboratory [99] used PCM to control the precolor outlet temperature. The study highlighted the accuracy and effectiveness for PCM, however this study based on simplified mathematical model not a complex dynamic model. Furthermore, Bonne et al. [100] presented a simplified PCM control model for a 70KW_e sCO_2 open power cycle, which was designed to control the net power while maintaining the TIT at the reference value. In addition, a reduced-order dynamic model for a closed sCO_2 power cycle was used to test the control strategy. The result showed that the PCM control scheme has the capabilities to handle nonlinearity and system coupling. However, this study only served as foundational research for applying PCM to the sCO_2 power cycle. In contrast, Bone et al. [101] used the findings and cycle layout of Bonne's study and explained the efficiency of PCM in controlling the high-pressure side of the sCO_2 power cycle, achieving efficient dynamic performance compared to traditional PID control systems. Although the study is a numerical simulation, it raises concerns about real-world capability.

Similarly, Albright and Liese [102] demonstrated the effectiveness of PCM in improving load-following capabilities for the recompression sCO_2 power cycle, but the author didn't address the practical challenges of implementing this strategy in a large-scale plant or in the real world.

As previously noted, DRL for the SCBC has not been extensively explored; however, one study has developed an offline DRL approach for SCBC. The study conducted by Wang et al. [103] involved the development and application of a DRL controller to regulate the MCIT by changing the water flow rate in the cooler. The research assessed the efficacy of the DRL controller in comparison to a conventional PID controller and a linear model predictive controller (LMPC). The authors validated the dynamic model of the cooler through experimental data obtained from their test bench for both the cooler and compressor. The result show that the DRL surpasses the PID controller, yet it does not achieve the performance level of the LMPC, exhibiting temperature accuracies of $\pm$ 0.15 for the DRL and $\pm$ 0.05 for the LMPC, respectively. LMPC achieved the highest accuracy in control; however, it required real-time resolution of optimisation problems, resulting in considerable fluctuations in control input (cooling water flow rate) and heightened computational demands. The DRL controller, trained offline, required no real-time optimisation and exhibited the fastest execution time in simulations. While its control precision was slightly inferior to that of LMPC, DRL showed significant extrapolation capabilities and generalisation potential. The authors propose that augmenting the training dataset and enhancing parameter tuning may enable DRL to surpass the precision and adaptability of conventional and model-based controllers, indicating a promising avenue for future research in sCO_2 cycle control.

Finally, Chen et al. [104] proposed an ANN method to predict the pressure drop, which alleviates model complexity and thereby reduces computational time for three combined SCBC-ORC designs for a 50 MW_e coal-fired power plant. The proposed ANN grey-box model is accurate in simulating the power generation system with a maximum error of less than 0.22 %, and it reduces the CPU time for coal-fired power plant systems by 50 %–60 %.

Table 4 presents the Kay studies implementing an advanced control strategy, all of which are numerical in nature. Conversely, all the dynamic models used in advanced control studies were thermal power change and load dynamic models without accounting for the startup, shutdown, and emergency scenarios. Notably, there isn't a wide range of advanced control strategies for sCO_2 power cycles like there is for the basic cycle. This lack of variety highlights the need for more research into advanced control methods to make sCO_2 power cycles more robust and flexible. The accuracy for the SCBC control model can be optimized by involving a data-driven approach such as DNN with minimum computation time. Furthermore, some of the authors suggest that the DRL has the potential to be a successful approach for determining the optimal load following a control strategy due to its capacity to resolve intricate control problems.

5.1. Challenges and opportunities in control strategies for SCBC

The sCO_2 power cycle is capable of generating electricity and heat and can also be integrated into multi-energy systems, including hydrogen production. Most of the reviewed studies concentrate on electricity generation utilising the sCO_2 cycle and employing heat sources including concentrated solar power, waste heat, fossil fuels, or

Table 4
Summary of the advanced control strategies for SCBC.

Cycle	Power [MW_e]	Heat source	Controller type	Control parameters	Control strategy	Dynamic model	Exp./Num.	Ref.
RC-DRC-SCBC	2	CSP	- PI	TIT	- INV-FTM - INV −CTM	Thermal Power Change	Numerical	[94]
SR-SCBC	0.2	CSP	- PID	- TIT	- Fixed −INV - INV-ESC - INV-ILC	Solar Heat Change	Numerical	[95]
SR-RC-SCBC	8.5	CFPP	- PID	- P_{ms} - P	- μ_{TG} - $\mu_{TG} + G_{hot}$ - $\mu_{TG} + G_{ES}$ - DCS ($\mu_{TG} + G_{hot}$) - DCS ($\mu_{TG} + G_{ES}$)	Load Following	Numerical	[97]
RC-DRC-SCBC	0.37	Comb	- PI - PID - GS-PID	- TIT - MCIT - CS - SR	- HS - BCV - CBFV - INV+(SR-ANN) - TAC+(SR-ANN)	Load Following	Numerical	[98]

nuclear energy. The research conducted by Zhaozhi et al. [90] stands out, as it illustrates the simultaneous generation of mechanical and electrical power for marine propulsion. The literature indicates a clear trend towards optimising trade-offs between cycle efficiency and operational flexibility, especially under varying heat input conditions or load following; however, the consideration of carbon capture or direct CO_2 emissions reduction is not addressed before.

The earlier-mentioned studies for Milani et al. [62] and Luu et al. [55] proposed a control strategy to switch between solar heat sources and the backup fossil fuel during the peak sun hours. The authors didn't mention that this control strategy reduces CO_2 emissions, but indirectly, it reduces the reliance on fossil fuels to reduce carbon emissions. Moreover, the aforementioned study for Minh et al. [55] emphasised thermal efficiency and system stability as their primary objectives, and Wang et al. [98] investigated optimal split ratios to improve off-design performance, excluding environmental or carbon-related control metrics.

Moreover, The Allam cycle, which captures nearly 100 % of CO_2 emissions through its oxy-combustion process [13,105], primarily addresses control strategies in relation to plant operability and dynamic stability. While dynamic control systems have been created for demonstration-scale Allam cycle, existing studies do not provide a multi-objective control framework that explicitly addresses the dynamic trade-offs between carbon capture performance and other operational objectives, including efficiency and flexibility. This highlights a notable absence in the literature: although numerous sCO_2 systems possess the thermodynamic potential to facilitate low-carbon energy objectives, existing control strategies primarily focus on optimising energy performance. The incorporation of CO_2 capture goals into control, especially in hybrid or multi-energy contexts, is still not extensively investigated. Future research should focus on developing multi-objective control strategies that explicitly balance emissions reduction, efficiency, and flexibility to fully energy networks.

Despite the potential of DRL in controlling SCBC, numerous challenges remain. A significant concern is sample inefficiency; training DRL agents generally needs extensive interactions, that can be costly and impractical for high fidelity SCBC simulations or physical systems. Methods such as offline DRL, model-based RL, and simulation-to-reality transfers present viable solutions by minimising the necessity for real-time experimentation. Designing effective reward functions poses a challenge due to the need to balance competing objectives such as efficiency, safety, and response time. Inconsistent definitions of rewards can lead to unpredictable or dangerous behaviours. Multi-objective or hierarchical reward structures can improve reliability and performance. Current studies frequently neglect physical system constraints, including compressor maps and valve hysteresis, which are essential for safe operation. Integrating these constraints into training environments is crucial for practical applicability. Despite these challenges, the adaptability and generalisation capabilities of DRL present valuable opportunities, particularly when integrated with conventional methods, such as PID control, to improve robustness and practicality.

A further limitation for AI-driven control strategies is their opaque nature; specifically, the DNN employed in the DRL usually suffers from a deficiency in transparency, which hinders the understanding of certain control decisions. This oversight limitation may cause a safety issue in critical systems such as SCBC, where it is important for the operator to trust and validate the system's conduct. Consequently, enhancing the system transparency can be achieved by including explainable AI tools or by integrating physics-informed models. These tools are essential for ensuring the safety and reliable implementation of AI-driven control in practical energy systems.

Moreover, the advanced control strategies used for the sCO_2 power cycle are very limited. In contrast, the advanced control strategies for micro gas turbines (MGT) are wider and may be suitable for the sCO_2 power cycle. For instance, it is recommended to incorporate the PCM into the advanced control strategy for MGT to control TIT, surge margin, and shaft speed [106,107]. Meanwhile, fuzzy PID controllers proved to be more effective than traditional PI and PID controllers in controlling MGT shaft speed and temperature [108]. Finally, researchers conducted a comparative analysis between the fuzzy neural network (FNN) adaptive controller, the fuzzy logic controller, and the fuzzy PID controller. The FNN adaptive controller demonstrated improved effectiveness and robustness in controlling speed and turbine outlet temperature (TOT) [109,110,111].

Furthermore, it is important to acknowledge that the majority of most of the control strategies studies presented, although comprehensive experimental validation is difficult, numerous research studies have validated their dynamic models based on data from experimental test loops. For instance, research in references [41,97,68], and [59] employed data from testing experimental test facilities to corroborate either whole system models or particular components.

On the other hand, alternative approaches have been employed in other research to verify model accuracy, including sensitivity analyses, scaling validated component-level data, or benchmarking models against proven numerical tools [92,93]. While these methods may not offer complete experimental validation, they enhance trust provide confidence in the models and control strategies proposed.

6. Conclusion

Recently, the supercritical Carbon Dioxide (sCO_2) Brayton cycle has gained attention in various industrial sectors, particularly in the electricity production field, due to its unique features such as compactness, high efficiency, ability to deal with various heat sources, among other advantages. This paper presented a detailed review of the sCO_2 Brayton cycle's control strategies, including the basic control strategies for startup/shutdown and off design performance, combined control strategies, and advanced control strategies. The main conclusions and challenges are presented as follows:

1. The main control strategies used for the sCO_2 Brayton cycle were inventory control, valve control, heat and cold source control, and turbomachinery rotation speed control. All of the aforementioned strategies were implemented numerically, except for one study that implemented experimental with a small scale for the startup dynamic model. In addition, the controller used in the previous studies was PI/PID. However, further work needs to be conducted more experimentally with a wide range of working conditions.
2. The basic control strategies were limited, and in order to overcome this, some studies tried and proposed a combination of these control strategies, but all of these studies were numerical and focused only on the load following the dynamic model. So, to enhance the reliability, these combined strategies need to be tested experimentally, and more combined strategies need to be considered for the startup, shutdown, and emergency seniors.
3. Finally, some studies used advanced control strategies such as Extremum-Seeking Control (ESC), Iterative Learning Control (ILC), dual PID, DRL, and ANN, but the number of these studies and combined control strategies was very small compared to the basic control strategies, which means further research needs to be conducted in these two techniques. Meanwhile, enhancing the accuracy of SCBC control can be accomplished through the utilization of data-driven techniques such as Deep Neural Networks (DNNs), which are renowned for their efficient computational speed. DRL's promise in designing optimal load-following techniques is highlighted because of its ability to tackle intricate control problems.

A future study should focus on experimental validation of both combined and advanced control strategies for the sCO_2 power cycle, especially under the start-up and shutdown and emergency scenarios to ensure real-world applicability. While there are few advanced control techniques available for the sCO_2 cycle, it is possible to modify those used in Micro Gas Turbines (MGT) to achieve this purpose. Research has shown the effectiveness of Predictive Control Models (PCM) and fuzzy PID controllers in regulating MGT parameters. Conversely, FNN adaptive controllers have demonstrated higher effectiveness in controlling MGT speed and Turbine Outlet Temperature (TOT). Ultimately, the creation of a wide variety of data-driven and AI-based models, including DNN and DRL frameworks, could encourage real-time optimisation and adaptive responses, improving the reliability and flexibility of the sCO_2 power cycle across various operational scenarios.

CRediT authorship contribution statement

Reem H. Ahmed: Writing – original draft, Software, Investigation, Conceptualization, Writing – review & editing, Validation, Methodology, Data curation, Visualization, Resources, Formal analysis. **Jafar Al-Zaili:** Writing – review & editing, Supervision. **Abdulnaser I. Sayma:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Reem Ahmed reports financial support was provided by UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding Guarantee for the project "ISOP" with grant agreement 101073266. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was funded by UK Research and Innovation under the UK government's Horizon Europe funding Guarantee Scheme [Grant number EP/X04131X/1] as part of a collaboration with ISOP project [Grant Agreement No. 101073266] funded by the European Union's Horizon Europe research and innovation programme, Marie-Sklodowska-Curie Actions.

Data availability

No data was used for the research described in the article.

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