
This paper adds an exergy analysis of the novel SOLRGT solar-assisted power generation system proposed and described in detail in Part I of this study (Zhang and Lior, 2012, “Use of Low/Mid-Temperature Solar Heat for Thermochemical Upgrading of Energy, Part I: Application to a Novel Chemically-Recuperated Gas-Turbine Power Generation (SOLRGT) System,” ASME J. Eng. Gas Turbines Power, Accepted. SOLRGT is an intercooled chemically recuperated gas turbine cycle, in which solar thermal energy collected at about 220°C is first transformed into the latent heat of water vapor supplied to a reformer, and then via the reforming reactions to the produced syngas chemical exergy. This integration of this concept of indirect thermochemical upgrading of low/mid temperature solar heat has resulted in a high efficiency novel hybrid power generation system. In Part I it was shown that the solar-driven steam production helps improve both the chemical and thermal recuperation in the system, with both processes contributing to the overall efficiency improvement of about 5.6%-points above that of a comparable intercooled CRGT system without solar assist, and nearly 20% reduction of CO₂ emissions. An economic analysis of SOLRGT predicted that the generated electricity cost by the system is about 0.06 $/kWh, and the payback period about 10.7 years (including two years of construction). The exergy analysis of SOLRGT in this (Part II) paper identified that the main potentials for efficiency improvement is in the combustion, the turbine and compressors, and in the flue gas due to its large water vapor content. Guided by this, an improved solar-assisted zero-emissions power generation system configuration with oxy-fuel combustion and CO₂ capture, ZE-SOLRGT, is hereby proposed, in which the exergy losses associated with combustion and heat dumping to the environment are reduced significantly. The analysis predicts that this novel system with an 18% solar heat input share has a thermal efficiency of 50.7% and exergy efficiency of 53%, with ~100% CO₂ capture. [DOI: 10.1115/1.4006086]

Keywords: hybrid power system, solar heat, CO₂ capture, zero-emissions power generation, exergy analysis

1 Introduction

Part I of this paper published separately [1] described the proposal and detailed analysis and performance of a novel solar-assisted chemically-recuperated gas-turbine power generation system (SOLRGT) described in Fig. 1. This paper contains its exergy analysis that led to yet another novel high-efficiency solar assisted power generation system that also captures the produced CO₂. A detailed system introduction is thus available in Part I of the paper [1], but is briefly summarized here.

Instead (or in addition) of previously proposed and implemented thermal integration of solar heat into the power generation systems by some physical heat absorption process such as evaporation and recuperation, by which it is converted to internal heat of the working fluid, the solar heat input to SOLRGT is integrated thermo-chemically into the endothermic reactions of reforming, wherewith the thermo-chemical integration converts the absorbed solar heat into the working fluid chemical energy, thus achieving an upgrading of the solar heat for manufacturing a fuel that can then be burned to attain a high temperature.
The reformed fuel in SOLRGT is methane and its reforming reaction with steam is highly endothermic and produces syngas composed of CO and H₂, which is then used in an advanced thermochemically-recuperated gas turbine power generation system, where direct use of low temperature solar heat at about 200 °C–300 °C is thus not as effective as the use of the high temperature heat generated by fuel combustion. Thus the low/mid temperature solar heat is first transformed to the vapor (steam) latent heat, and then further transformed to the syngas chemical energy via the reforming reaction, enabling this upgraded generated fuel to be burned and used in a high efficiency power generation system. The SOLRGT system analysis described in Part I shows that the same electricity output as that generated by a conventional chemically recuperated gas turbine (CRGT) system without solar heat contribution is attained, but with the clear advantage of reducing the fuel input by about 20%. The SOLRGT operating conditions and the major performance results are summarized in Table 1, which is copied from Part I [1].

To try to improve the solar-assisted thermochemical upgrading potential of such power generation systems we conduct in this paper (Part II) an exergy analysis of SOLRGT, that should guide thermodynamic improvement paths by identifying the exergy losses in each main component and examining the results. As shown below, this analysis guided us to the proposal of a rather different and yet another high-efficiency novel power generation system that is also solar-assisted but uses oxy-fuel combustion to also capture the generated CO₂, which we call ZE-SOLRGT (the ZE stands for zero-emissions).

The SOLRGT system in Fig. 1 was simulated using the assumptions described in Part I of this study [1]. The performance of the system is summarized in Table 1. A detailed discussion of the results can be found in Part I.

As also shown in Part I [1], the thermodynamic performance criteria shown in Table 1 are defined below.

The thermal efficiency of the system:

\[ \eta_{th} = \frac{W_{net}}{Q_{in} + Q_{sol}} = \frac{W_{net}}{m_f \cdot LHV + Q_{sol}} \] (1)

where \( W_{net} \) is the net electric power produced by the SOLRGT system, defined as the gross power output minus power consumption from all the compressors, the pump and the mechanical loss, and \( Q_{in} = m_f LHV \) is the fuel low heating value input, while \( Q_{sol} \) is the absorbed solar heat by steam generation.

Since the system inputs consist of the methane chemical energy and solar heat, and the output is mechanical energy, all different in their energy qualities, exergy rather than energy efficiency is more suitable for the system performance evaluation. To be consistent with the thermal efficiency of the conventional CRGT cycle without solar heat input, an equivalent exergy efficiency is defined in Eq. (2), assuming that the methane exergy is approximately equal to its lower heating value \( LHV \) and the exergy of the solar heat at a temperature \( T_{sol} \) is calculated as the maximal work availability between \( T_{rad} \) and the ambient temperature \( T_0 \), i.e., \( Q_{sol}(1 - T_0/T_{sol}) \). When the solar input \( Q_{sol} \) is zero, \( \eta_e \) is equal to the thermal energy efficiency (just as in a conventional fossil fuel power plant), and is called system efficiency hereafter.

\[ \eta_e = \frac{W_{net}}{Q_f + Q_{sol}(1 - T_0/T_{sol})} = \frac{W_{net}}{m_f \cdot LHV + Q_{sol}(1 - T_0/T_{sol})} \] (2)

The contribution of the low/mid temperature level solar heat can be measured by its share in the system total energy input:

\[ X_{sol} = \frac{Q_{sol}}{Q_f + Q_{sol}} = \frac{Q_{sol}}{m_f \cdot LHV + Q_{sol}} \] (3)

The solar exergy share therefore is:

\[ X_{e,sol} = \frac{Q_{sol}(1 - T_0/T_{sol})}{m_f \cdot LHV + Q_{sol}(1 - T_0/T_{sol})} \] (4)

The net solar-to-electricity efficiency is defined to evaluate the performance of conversion from solar heat to total power output [2]:

\[ \eta_{sol} = \frac{W_{net} - W_{ref}}{Q_{sol}} = \frac{W_{net} - Q_f \eta_{e,ref}}{Q_{rad}} \] (5)

in which \( W_{ref} \) is the power output generated by the referenced system, which was chosen to be the inter-cooled chemically recuperated gas turbine (IC-CRGT) system (the same configuration as SOLRGT but without solar heat input) with the same methane input, \( W_{rad} = Q_f \cdot \eta_{e,ref} \); \( Q_{rad} \) represents the total solar energy incident on the solar concentrator.

The fossil fuel savings in comparison with the conventional IC-CRGT power plant, for generating the same amount of electricity, is defined as the fossil fuel saving ratio:

\[ SR_f = \frac{W_{net}/\eta_{e,ref} - Q_f}{W_{net}/\eta_{e,ref}} = 1 - \frac{W_{ref}}{W_{net}} \] (6)
Table 2  Exergy analysis result of the SOLRGT cycle (based on 1 kmol/s CH₄)

<table>
<thead>
<tr>
<th></th>
<th>[MW]</th>
<th>[%]</th>
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</thead>
<tbody>
<tr>
<td>EXERGY INPUTS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>844.8</td>
<td>91.3</td>
</tr>
<tr>
<td>Solar heat</td>
<td>79.9</td>
<td>8.6</td>
</tr>
<tr>
<td>EXERGY OUTPUT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power generation</td>
<td>461.9</td>
<td>49.9</td>
</tr>
<tr>
<td>EXERGY LOSSES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustor (COM)</td>
<td>235.4</td>
<td>25.4</td>
</tr>
<tr>
<td>Reformer (REF)</td>
<td>9.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Recuperator (REP)</td>
<td>10.8</td>
<td>1.17</td>
</tr>
<tr>
<td>GT compressors and turbine</td>
<td>113.5</td>
<td>12.3</td>
</tr>
<tr>
<td>Economizer (ECO)</td>
<td>13.9</td>
<td>1.5</td>
</tr>
<tr>
<td>Water pump &amp; methane compressor</td>
<td>6.6</td>
<td>0.72</td>
</tr>
<tr>
<td>Flue gas</td>
<td>64.5</td>
<td>6.97</td>
</tr>
<tr>
<td>Mechanical loss</td>
<td>9.4</td>
<td>1.02</td>
</tr>
</tbody>
</table>

Using Eq. (3) and (6), the replacement of fossil fuel by solar energy is expressed as:

\[
R_f = \frac{W_{net}/\eta_{ref} - Q_f}{Q_{sol}} = SR_f \frac{W_{net}/\eta_{ref} - Q_f}{Q_f} = \frac{SR_f - 1}{SR_f} \frac{1 - X_{sol}}{X_{sol}}
\]

Similarly, the replacement of fossil fuel by solar exergy is expressed as:

\[
R_{fe} = \frac{W_{net}/\eta_{ref} - Q_f}{Q_{sol}(1 - T_0/T_{sol})} = \frac{R_f}{1 - T_0/T_{sol}}
\]

2  Exergy Analysis

An exergy analysis was preformed to identify the exergy losses in the SOLRGT system and thereby obtain guidance for further system improvement. The dead state is defined as 25 °C/1.013 bar. The exergy efficiency is defined as Eq. (9).

\[
\eta_{ex} = \frac{W_{net}}{E_f + Q_{sol}(1 - T_0/T_{sol})}
\]

where \(E_f\) is the fuel chemical exergy input. Table 2 presents the key results for the specific fuel input rate of 1.0 CH₄ kmol/s. The solar exergy share \(X_{sol}\) under these conditions is found to be <9%, much smaller than its thermal share of 20.3% because of its relatively low temperature.

As expected, the largest exergy loss occurs in the combustor, followed in magnitude by the exergy losses of the gas turbine compressors and turbines. In the gas turbine compressors and turbines, the coolant air extraction and re-introduction for blade cooling increases the exergy loss. The flue gas contains latent heat associated with the water vapor (23.7 mol%), and it is exhausted at a relatively high temperature of 163 °C, so the flue gas exergy is also a big exergy loss and takes the third place. Since the calculation of the exergy efficiency in Eq. (9) is based on the absorbed solar exergy, the collector and evaporator inefficiencies are not taken into account in this analysis.

2.1 Exergy Utilization Diagram (EUD). The concept of “energy level,” \(A\), is employed to represent the quality of released or accepted energy for a given process [3,4]. It is defined as the ratio of exergy change to energy change

\[
A = \frac{\Delta E}{\Delta H} = 1 - T_0 \frac{\Delta S}{\Delta H}
\]

that shows the effect of enthalpy changes on the concomitant exergy ones.

For the heat transfer process, defining the entropic average temperature as \(T = \Delta H/\Delta S\), gives

\[
A = 1 - \frac{T_0}{T}
\]

In this case, \(A\) is equivalent to the power produced in a Carnot cycle working between \(T\) and \(T_0\) with unit heat input, and is defined as the availability factor or the energy quality [3,4]. The indirect upgrading of the low/mid temperature solar heat can be depicted as shown in Fig. 2.

From 1 to 2 is the process of steam generation, the collected solar heat transforms into the steam latent heat, experiencing the energy level drop from \(A_{sol}\) to \(A_2\) because of the heat transfer temperature difference. Process (2/2') is the steam reforming process (CH₄ + H₂O ⇌ CO + 3H₂). The generated steam at about the temperature of 220 °C with an energy level of about 0.4 is heated, part of the steam takes part in the chemical reaction, the energy level of the steam is elevated partially chemically and partially physically and thus transforms into syngas chemical exergy (from 2 to 3), i.e., from \(A_2\) to \(A_{syn}\). At the same time part of the turbine exhaust heat is recuperated by the chemical reaction and converted to the syngas chemical exergy as well (2'-3). The upgrade of the energy levels of both steam and turbine exhaust heat is driven by the energy level drop of the methane that is at about 1.04 to syngas at about 0.96 (depends on its composition) (2'-3'). Finally, the process 3–4 is the combustion in which the syngas chemical exergy converts into the internal heat exergy, and the energy level drops to that of the combustion products at the TIT.

Based on the concept of energy level, Jin et al. [5] proposed the graphical exergy analysis method - Exergy Utilization Diagram (EUD) [5]. In each energy-transformation system, the EUD method identifies an energy donor and an energy acceptor. Energy is released by the former and is accepted by the latter as \(\Delta H\), and the energy quality of the donor \(A_d\) and acceptor \(A_a\) are paired. By plotting \(A_d\) and \(A_a\) versus the transformed energy \(\Delta H\), we obtain the exergy loss represented as the area in between. Compared with the \(T-Q\) diagram, which interprets the process from the energy point of view, the EUD does it from both the energy and exergy ones; \(\Delta H\) (or \(Q\)) on the abscissa represents the transferred energy quantity related to the first law of thermodynamics; while \(A\) on the ordinates denotes the corresponding energy quality (exergy) and is related to the second law of thermodynamics. In addition, \(\Delta A = A_d - A_a\) is a parameter that represents the driving force to make the process proceed. This method obviously provides more information than just the exergy difference between the entry and exit states, and is explained and used below for this power system in some detail.
Comparing with direct combustion of hydrocarbon fuel like methane with air, burning of syngas has the following two advantages:

1. The reforming-created syngas has higher heating value, as shown in Fig. 3 by the width of the fuel energy donor lines, the heat released is 881 kW/(mol/s CH₄) for syngas combustion (the length of c-d') and 806 kW/(mol/s CH₄) for methane direct combustion (the length of c-d) at the same TIT of 1308 °C. Both the recuperated gas turbine exhaust heat and the latent heat of the reacted steam contributed to the heating value increase. For methane fuel flow rate of 1 mol/s, totally 98.6 kW turbine exhaust heat is recuperated in the reformer, of which about 26.5% was converted into physical enthalpy (indicated by temperature rise), and 73.5% is converted into the produced syngas chemical exergy by providing the heat needed for reforming. The H₂O/CH₄ mole ratio in the reformer is 6.1, 11.9% of the steam generated by solar heat takes part in the reaction and changes into products, the other 88.1% takes part in the physical heat recuperation and achieves a corresponding energy level elevation as well. The reforming reaction upgrades the absorbed turbine exhaust heat directly, and the low-mid level solar heat indirectly, to the syngas chemical exergy, and then combustion transforms them into the high-temperature thermal heat at energy level of A_{TR}. The presence of large amount of steam not only serves as a medium for solar heat transformation but also strengthens the methane conversion and lowers the combustion NOₓ emissions to a very-low value [8–12].

2. The reforming reaction creates syngas that has a lower energy level than methane (by comparing in Fig. 3 the height of line a-b for methane and a'-b' for syngas), so the combustion process of syngas has a lower energy level difference (ΔA = A_{syngas} − A_{TR}) between the energy donor and the energy acceptor. Considering that the temperature, pressure and composition of the combustion products remain approximately the same, the exergy destruction in the conversion from chemical into thermal energy is therefore lower in syngas combustion than that in the unreformed methane fuel, as shown in Figs. 2 and 3. That creates a gain from the combustion of syngas as compared with the direct combustion of methane. In this study, the exergy loss reduction due to syngas combustion (the mixing loss has not been taken into account) is 27.4 kW/(mol/s CH₄), which is equivalent to 3% of the exergy efficiency enhancement, and this profit from combustion of syngas could be expected to increases as the methane conversion rate increases. In the calculations in this paper the methane conversion rate is 37.8%, and higher reforming temperature and steam addition and lower pressure favor the conversion rate, thus showing a direction for reducing the combustion exergy loss.

The EUD diagram of the turbine exhaust heat recuperation process is shown in Fig. 4. As mentioned in Part I [1], the integration of the solar heated steam evaporation process allows the turbine exhaust to be recuperated using only the sensible heat source inside the reformer (REF), the recuperator (REP) and the economizer (ECO) in HRSG, thus obtaining an improved thermal match between hot and cold streams, leading to relatively small exergy loss in these heat exchangers. Totally 484 kW/(mol/s CH₄) heat is recovered in these three heat exchangers with 34 kW/(mol/s CH₄) exergy loss. Flue gas, on the other hand is associated with a high exergy loss of 64.5 kW/(mol/s CH₄), represented by the shaded area in Fig. 4. The flue gas exhausts at a temperature of 163 °C, and although it is at an average energy level lower than 0.2, the high mole fraction of water vapor in it associates it with large latent heat loss. As shown in Fig. 4, the water vapor starts a phase change from steam to water at a temperature about 68 °C, dumping a large amount of latent heat to the environment. This suggests

Figures 3 and 4 show the EUD diagrams for the combustion, and the turbine exhaust heat recuperation process, respectively. The two graphs are drawn in the same scale for easy comparison. In Fig. 3, the EUD diagram for the combustion process, the oxidation of the unreacted syngas acts as the energy donor (curve A_{syngas}), and the heating process of the mixture of reactants and products acts as the energy acceptors (A₂), which are heated to the specific combustion temperature of TIT. The exergy loss by mixing of the reactants is found to be 48.3 kW/(mol/s CH₄) and is indicated by the rectangular area in Fig. 3. With the height of the rectangle being unity, not only its area but also its width represents the amount of the exergy loss of mixing, but one should be aware that the width on the abscissa has nothing to do with the quantity of energy transformed since ΔH for mixing is generally near zero. The exergy loss of mixing is relatively large in this case because of the high fraction of vapor, 68%, in the syngas.

Apart from the mixing loss, the combustion exergy loss is mainly due to the degradation of the high chemical exergy of the fuel (with higher A₂) to the lower exergy of the heat (with much lower A_{TR}) produced by the combustion (see Refs. [6,7]), as shown by the shaded area between the energy donor and acceptor.
that the steam introduction amount is a key parameter to the system performance, and its effect is examined below.

### 2.2 The Effect of Steam-Air Mass Ratio

Figure 5 shows the exergy loss variation with the steam-air mass ratio $X_s$. The increase of the amount of added steam, as indicated by increasing $X_s$, has the following consequences:

1. **The combustion exergy loss is reduced.** In Fig. 5, we separate the combustion exergy loss into two parts, i.e., the exergy loss related to the destruction of chemical exergy and heat transfer, and the mixing loss. As mentioned before, the two-step combustion (reforming and syngas combustion) may reduce the combustion-related exergy destruction compared with the direct methane combustion. Supply of more steam on one hand increases the mixing exergy loss, but on the other hand favors the methane conversion, increasing the syngas production, and the latter dominates, so the overall combustion exergy loss reduced.

2. **The compressor and turbine exergy loss is reduced.** Though increasing water vapor addition increases the turbine working fluid flow and thus requires more blade cooling, the dominant effect is that the increased flow rate of the working fluid produces more power.

3. **As $X_s$ is increased, this first reduces the flue gas exergy loss till it reaches a minimum at a certain value of $X_s$ and then the loss rises as $X_s$ is increased further.** It can be explained by noting that at low $X_s$, there is less water brought into the system, and thus the turbine exhaust heat is not fully recuperated in the HRSG and therefore exhausts at a higher temperature (for example, the flue gas temperature is 210°C when $X_s = 0.06$), leading to a higher exergy loss to the environment. For high $X_s$, the exhaust heat is fully recovered thermally by producing more steam, and the flue gas temperature thus decreases. However, the exhaust gas then contains more latent heat associated with the large amount of water vapor (exhausting at 100°C, the water vapor mole fraction is 34.3% in the flue gas when $X_s = 0.256$), leading to an increased exergy loss to the environment as well.

### 2.3 Exergy Analysis Results Guidance for System Improvement

From these observations we can conclude that for lower $X_s$, the flue gas exergy loss is mainly associated with the sensible heat loss, indicating that heat recuperation was not fully exploited. Hence, using the unused part of the exhaust heat to replace part of the solar heat for the water evaporation reduces the solar heat use, thus reducing the required collector area. This leads to a significant reduction in the plant investment cost since the solar collectors generally accounts for 40–50% of the capital cost for the entire investment in a solar thermal power plant [1,2]. This reduction of the solar heat input comes from the exhaust heat recuperation rather than from a higher fossil fuel input. Figures 6 and 7 show the effect of replacing part of the solar energy with the excess exhaust heat. We note that increasing the exhaust heat recuperation reduces only the solar energy input share and has no impact on the power generation and fossil fuel input rates; it therefore improves the system overall performance, decreasing the solar heat share while increasing the solar-to-electricity and the global system efficiencies, and also the replacement of fossil fuel by solar energy/exergy, $R_f$ and $R_{fe}$.

For high $X_s$, the flue gas contains a high fraction of steam, and the exergy loss is mainly associated with much latent heat dumped to the environment. This suggests that the exergy loss may be reduced by recycling part of the flue gas to bring its latent heat back to the combustor as done in some oxy-fuel combustion.
power systems. Thus the exergy analysis of SOLRGT led us to consider replacing the air-based combustion in SOLRGT by oxy-fuel combustion, which has often been considered to accomplish more effective CO₂ capture, and which would thus also add another important positive attribute to this power generation. Either H₂O or CO₂ can be used in the oxy-fuel system as the main working fluid, and the combustion flue gas is also a mixture of H₂O and CO₂. Since the steam fraction in the flue gas is very high already in the SOLRGT system, it is advantageous to choose H₂O as the main working fluid. Beside reduction of the flue gas exergy loss and the ability to capture CO₂, further consideration for selecting steam as the working fluid and oxy-fuel combustion includes: (1) the steam cycle has the advantage of high pressure ratio and low back-power ratio, (2) solar heat collection can easily be integrated for steam generation, (3) steam can be used for high-temperature turbine blade cooling, and the required coolant amount is reduced because of the higher heat capacity of steam than that of air, and especially, (4) the mixing exergy loss in combustion will be reduced when the reformed syngas (which is enriched with steam) mixes with steam working fluid rather than with air.

As shown in Fig. 8, an oxy-fuel cycle (named ZE-SOLRGT by us) is thus proposed, which employs steam as the main working fluid. A Graz-like cycle [13–15] is adopted as the core of the power system, where the main advantage of this configuration is the combination of a high-temperature Brayton top cycle with a Graz-like cycle, HPT, LPT and HPST. The high temperature turbine generated power, compared with 34.8% in the SOLRGT cycle. In the ZE-SOLRGT cycle, the recycled working fluid that is sent to the reformer to increase the H₂O/CH₄ ratio in the reforming reaction.

The solar heat is input upstream of the steam superheater. The collected solar heat provides heat for water evaporation. Since the generated steam is at a much high pressure of 150 bar with a saturation temperature of 341 °C, a correspondingly higher solar heat temperature is required than in the SOLRGT system.

We note that the following energy and exergy analyses of ZE-SOLRGT also take into consideration the energy and exergy required to produce the needed oxygen, based on [13–17]. The exergy analysis results in Table 3 suggests that with the same fossil fuel input, the exergy efficiency of the ZE-SOLRGT cycle is 53% with 100% CO₂ capture, remarkably more than 3%-points higher than that of SOLRGT without CO₂ capture. The combustion exergy loss drops from 235.4 kJ/(mol CH₄) in SOLRGT to 206.1 kJ/(mol CH₄) in the ZE-SOLRGT cycle, which includes a mixing exergy loss drop from 48.3 kJ/(mol CH₄) to 33.3 kJ/(mol CH₄). The drop of the mixing exergy in the ZE-SOLRGT system is mainly because of the similarity of the stream compositions before mixing, since both the syngas and the recycled working fluid from the compressor are H₂O-enriched streams.

As shown in Fig. 8, there are three turbines in the system in the Graz-part of the cycle, HPT, LPT and HPST. The high temperature combustion gas first expands in HPT to generate power, and then its exhaust heat is recuperated by reforming and steam superheating in turn. Only part of the flue gas is further expanded in LPT to vacuum and then condensed in the Rankine-like cycle, the remainder is recycled back via a compressor to the combustor without phase change and latent heat release. The non-condensable gases from the condenser are compressed and the combustion-generated CO₂ is captured. The recycled water is pumped to a high pressure of 150 bar and evaporated and superheated, with the produced steam expanded in HPST to generate additional power.

The steam needed for reforming is extracted at the proper pressure from HPST to mix with CH₄ to produce syngas in the reformer, which serves as the fuel to the combustor. Open-loop steam cooling is adopted for the HPT blade cooling, and the coolant steam is bled from the HPST turbine outlet. The remaining HPST exhaust steam is injected in to the combustor as done in the Graz cycle, but this is optional. For the calculations in this paper, all of the HPST exhaust except that needed for HPT blade cooling is sent to the reformer to increase the H₂O/CH₄ ratio in the reforming reaction.

Fig. 8 Process flowsheet of the ZE-SOLRGT cycle
steam. In the ZE-SOLRGT system, the ratio of the coolant steam mass flow rate to the turbine inlet working fluid mass flow rate is 13% compared with 17% in the SOLRGT cycle. The reduction of the exergy loss to the environment is also significant. In the SOLRGT system, the flue gas related exergy loss is as high as 64.5 kJ/mol CH₄, while in the ZE-SOLRGT system, the exergy loss in the condenser is only 38.9 kJ/(mol CH₄) because the condensation releases heat at a relatively low temperature of 35 °C. In addition, 59% of the HPT exhaust working fluid is recycled, taking its latent heat back to the combustor; thus significantly reducing the condenser load.

The ZE-SOLRGT system exhibits a thermal efficiency of 50.7% and equivalent exergy efficiency (Eq. (2)) of 55.5%, with ~100% CO₂ capture and 18% solar heat input share. The performance is far better than that of a gas-stem combined cycle at the same TIT level, in which the thermal efficiency drops to about 46–48% when using a chemical absorption process for flue gas capture and accomplishing only about 90% CO₂ capture. Further details about the analysis of the ZE-SOLRGT system can be found in Ref. [18].

### 3 Concluding Remarks

A hybrid solar improved CRGT (“SOLRGT”) system, which integrates power generation with solar heat thermal and thermo-chemical conversion has been proposed in Part I of this study [1]. In this paper, an exergy analysis was conducted to identify the exergy loss in each main component and the potential for improvement, and the major exergy losses were found to be in the combustion, the turbine and compressors, and in the flue gas exhaust, which also incurs large exergy loss due to its large water vapor content that thus loses the latent heat and its exergy to the environment. Guided by the exergy analysis results, an improved cycle configuration with oxy-fuel combustion and CO₂ capture (named “ZE-SOLRGT”) is thus proposed, with steam as its main working fluid. Its power section is configured on a Graz-like cycle to take advantage of the combination of a high-temperature Brayton top cycle with a high pressure-ratio Rankine-like bottom cycle. After expanding in the high temperature turbine, only part of the flue gas is further expanded to vacuum and then condensed in the Rankine-like cycle, the remainder is recycled back via a compressor to the combustor, bringing its internal heat back to the combustor, thus significantly reducing the associated exergy loss to the environment. The mixing loss associated with combustion is reduced too because of the composition similarity of the streams entering the combustor. The analysis predicts that the ZE-SOLRGT system with an 18% solar heat input share has a thermal efficiency of 50.7% and exergy efficiency of 53%, with ~100% CO₂ capture.

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### Nomenclature

- **A**: energy level, ΔE/ΔH, Eq. (10)
- **CR**: methane conversion ratio
- **E**: exergy [kJ]
- **H**: entropy [kJ]
- **LHV**: lower heating value of fuel [kJ/kg]
- **m**: mass flow rate [kg/s]
- **p**: pressure [bar]
- **Q**: heat [kJ]
- **Rₜ**: steam-methane mole ratio to the reformer
- **Rₑ**: fossil fuel replacement per kJ solar energy input [kJ fossil fuel/kJ solar heat], Eq. (7)
- **Rₑ**: fossil fuel replacement per kJ solar energy input [kJ fossil fuel/kJ solar heat exergy], Eq. (8)
- **S**: entropy [kJ/K]
- **Sₑ**: fossil fuel saving ratio, Eq. (6)
- **T**: temperature [°C]
- **Tₑ**: turbine inlet temperature [°C]
- **Wₑ**: net power output [kJ]
- **Wₑₑ**: power output of the reference system [kJ]
- **Xₑₑ**: solar exergy input share, Eq. (4)
- **Xₑ**: steam-air mass ratio
- **Xₑₑ**: solar heat input share, Eq. (3)
- **ηₑ**: system efficiency [%], Eq. (2)
- **ηₑₑ**: exergy efficiency [%], Eq. (9)
- **ηₑₑ**: solar-to-electricity efficiency [%], Eq. (5)
- **ηₑₑ**: thermal efficiency [%], Eq. (1)

### Subscripts

- **a**: energy acceptor
- **d**: energy donor
- **f**: fuel
- **rad**: solar radiation
- **ref**: reference system
- **sol**: solar heat
- **syn**: syngas
- **Tₑ**: turbine inlet temperature
- **0**: environment state

### References


