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A novel concentrated solar power system using cascade steam-organic Rankine cycle and two-stage accumulators

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Abstract

A novel direct steam generation solar power system is proposed based on steam screw expander, cascade steam-organic Rankine cycle (SORC) and two-stage accumulators. The high temperature accumulator (HTA) enables smooth power conversion and stores thermal energy when solar radiation is available. The low temperature accumulator (LTA) is employed to elevate the storage capacity. One of the most remarkable features of the system is the heat discharge mode. First, heat is released via water vaporization in the HTA to drive the SORC. A maximum HTA temperature drop about 20 °C can be permitted. Then water at reduced temperature flows from the HTA to the LTA and heat is only used to drive the organic Rankine cycle (ORC). Nine organic fluids are adopted to analyze the system performance for seven regions worldwide. The results indicate that, compared with a conventional single-stage accumulator, the LTA can increase the storage capacity from 1.0 MWh_e to 8.4 MWh_e. The equivalent payback time in regard to the additional accumulator and collectors is estimated to be around 5 years in Phoenix and Lhasa. The LTA has great potential to improve the cost-effectiveness of the whole system.

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Keywords: Solar electricity generation system; Screw expander; Two-stage accumulators; Cascade steam-organic Rankine cycle; Equivalent payback time

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1. Introduction

Screw expander (SE) is able to handle working fluid at either liquid, binary phase or vapor state. It has excellent part-load behavior compared with turbo expander. Solar electricity generation system (SEGS) using steam SE and cascade steam-organic Rankine cycle (SORC) eliminates the superheater, and works at relatively low temperature and pressure. Solar power efficiency around 15% is achieved at a hot side temperature of 250 °C [1]. Particularly, when water is employed as the storage fluid, direct steam generation (DSG) and flexible operation can be facilitated and the SEGS has both thermodynamic and economic superiorities over an oil-related system [2]. However, there are also some challenges for the DSG-SEGS with water/steam accumulator.

First, the temperature drop of water available for heat discharge in the accumulator is restricted. Water is vaporized and the accumulator temperature decreases gradually. The inlet pressure of steam SE is declined consequently. The expander efficiency has a dramatic drop when the operating pressure is below the design, as demonstrated in many studies [3,4,5,6]. For a steam SE of design backpressure of 0.55 MPa, the operating pressure ratio will fall down from about 7.2 to 4.2 if the accumulator temperature changes from 250 to 220 °C. Regarding the low built-in expansion ratio of common SEs, a further decrement in the accumulator temperature will cause serious degradation of the SE performance.

Second, it is not easy to maintain steady operation of the bottom cycle during heat discharge, especially when an ORC turbine is deployed. The decreased accumulator temperature has negative effect on both the SRC and ORC. The mass flow rate through the SE decreases with the decrement in the inlet pressure. The heat released from the condensation of the exhaust may become inadequate to drive the ORC. ORC turbine is likely to suffer more than SE from the fluctuation of operating conditions. As a result, heat discharge may be accompanied by great thermodynamic irreversibility in the SORC.

Third, the accumulator plays an important role in the system cost-effectiveness. With 6.5 h storage for 1 MW_e SEGS, the material cost of the accumulator amounts to about 2.55 million RMB [2], which is comparable to the solar collectors'. The SEGS based on steam SE and DSG technologies will not be applicable if the accumulator is too expensive.

Storage is an important issue in SEGS. Two-stage and three-stage heat storage systems for efficient power conversion of turbine-driven DSG-SEGS have been investigated [7,8,9]. However, in these multi-stage storage units, the working fluid (water) and storage fluids (concrete, PCM, water, air, etc.) are separated and function independently.

In this work, an innovative SEGS using two-stage accumulators is proposed. Water acts as SRC working fluid, heat transfer fluid in the parabolic trough collector (PTC) and storage fluid for the SORC. It has a unique discharge process: First, water is vaporized in the high temperature accumulator (HTA) and circulated in the SRC. The total mass in the HTA is almost constant. Like a conventional single-stage sensible thermal energy storage unit, there are temperature and pressure drops during discharge. Second, when the temperature drop in the HTA reaches about 20 °C, water will be moved gradually to the low temperature accumulator (LTA). In this case, the HTA and LTA work similarly to a two-tank storage system. Fundamental of the proposed system will be illustrated in the following sections, and the thermodynamic performance and cost-effectiveness will be analyzed.

Nomenclature

A	aperture area, m^2	T	temperature, °C
D	diameter, mm	t	time, hour
G	solar radiation, W/m^2	W	power output, kW
h	enthalpy, kJ/kg	γ	isentropic index
m	mass flow rate, kg/s	θ	incidence angle,°
p	pressure, MPa	Φ	welding coefficient
P	price, RMB	$[\sigma]^t$	permissible stress, MPa
r	ratio		

2. System description

Fig.1 shows the DSG-SEGS using two-stage accumulators. Steam is generated in the PTCs. The power conversion subsystem is SORC. The top cycle is the SRC, which mainly consists of steam SE, condenser (HX1), pump (P1), PTCs and HTA. In parallel to P1, there is a LTA connected with a throttle valve. Space heating, absorption cooling and hot water generation can be facilitated via LTA if necessary. The bottom cycle is the ORC, composed of expander, condenser (HX2), pump (P3). Regarding the properties of common organic fluids, turbine is a better option in the ORC [1]. Compared with a single-stage accumulator based system [2], the novel SEGS possesses a LTA, more PTCs, etc. The additional devices are marked by red color. Thermodynamic states are marked by numbers with circle.

There are mainly two operating modes:

Mode 1: Heat collection and power conversion. The system works in this mode when solar radiation is available. V1, V2, V4 and V6 are open. P1, P2 and P3 run. Water is heated and partially evaporated in PTCs. Saturation steam goes into the SE, exporting power during expansion. The exhaust is condensed to saturation liquid in HX1, and is pressurized and sent back by P1 to the PTCs. The condensation heat is used to evaporate the working fluid in the ORC. Meanwhile, water in the LTA is pumped to the HTA, heated up through the PTCs. The mass in the LTA decreases gradually. Water leaving the solar field is at binary phase state on nominal conditions. However, it can be at either liquid or vapor state when the solar radiation fluctuates. Depending on the radiation, the flow rate through P2 can be adjusted to guarantee constant temperature in the HTA and steady power conversion of the SORC. The total electricity generation is $W_{SRC}+W_{ORC}$.

Mode 2: Heat discharge. When solar radiation is unavailable, heat will be released from the water via two steps. In the first step, water in the HTA is vaporized to drive both SRC and ORC. V1, V2, V4 and V7 are open. P1 and P3 run. The total electricity generation is $W_{SRC}+W_{ORC}$. In the second step, water in the HTA is transferred into the LTA through a throttle valve to drive the ORC. V3 and V5 are open. P3 runs. The total electricity generation is W_{ORC}.

The system with two-stage accumulators has many advantages, including:

- The storage capacity is remarkably increased. The temperature drop of water in a single-stage accumulator during discharge is limited in order to prevent serious performance degradation of the expanders. Its value shall be 20 °C, more or less. In the presence of two-stage accumulators, most of the water in the HTA can be transferred to LTA with a temperature difference exceeding 100 °C. It is possible to elevate the storage capacity by several times.

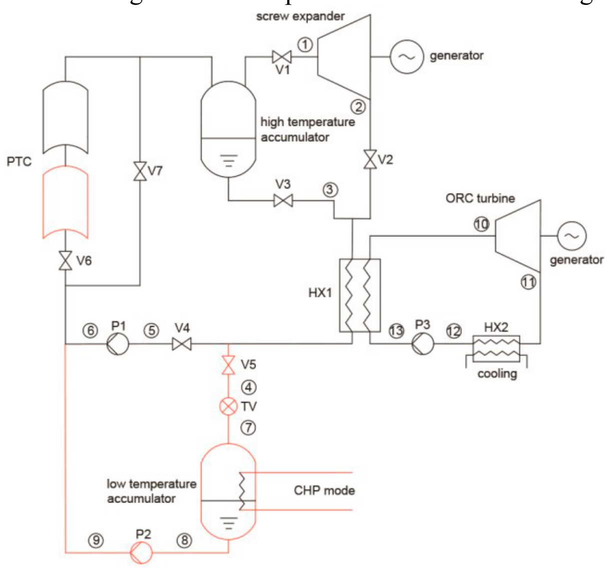

Fig.1. DSG solar power system using two-stage accumulators

- There is great potential to reduce the system payback period. Attributed to the LTA, much more electricity is generated per year for a given SORC system. In comparison with a system of single-stage accumulator, the additional investment is mainly on the LTA and PTCs. Regarding the low operating temperature and pressure, the investment on LTA should be slight, as shown in Section 4.3. More PTCs are required to store solar energy in the daytime, heating water from a low temperature in LTA to a high temperature in HTA. Nowadays, the PTC technology has reached a considerable degree of maturity, especially in the moderate temperature/pressure applications. Cost of solar PTC field operating at 400 °C has been lowered to about 1000 RMB/m^2 [10]. The SEGS will benefit from using the cost-effective PTCs to increase the annual electricity yield.

- Highly off-design operation of the SRC and ORC can be avoided. Since the storage capacity no longer relies solely on HTA, the temperature drop in HTA can maintain at a low level in the discharge process, enabling high efficiency of the expanders.

3. Mathematical equations

3.1. Mathematical equations

The SRC, ORC and cascade SORC efficiencies are defined by

$$\eta_{SRC} = (W_{SE} \cdot \varepsilon_g - W_{p1}) / [m_{SRC}(h_1 - h_6)] = W_{SRC} / [m_{SRC}(h_1 - h_6)] \tag{1}$$

$$\eta_{ORC} = (W_T \cdot \varepsilon_g - W_{p3}) / [m_{ORC}(h_{10} - h_{13})] = W_{ORC} / [m_{ORC}(h_{10} - h_{13})] \tag{2}$$

$$\eta_{SORC} = (W_{SRC} + W_{ORC}) / [m_{SRC}(h_1 - h_6)] \tag{3}$$

The SE efficiency is modelled by

$$\varepsilon_{SE} = \varepsilon_{SE,p} \cdot \frac{\varepsilon_D}{\varepsilon_{D,p}} \frac{(1 - r_{v,b}{}^{1-\gamma}) + (\gamma - 1)(1 - r_{v,b} / r_p)}{\gamma (1 - r_p{}^{1-\gamma/\gamma})} \tag{4}$$

Thermal efficiency (η_T) of the proposed system is expressed by

$$\eta_T = \eta_{SORC} \cdot \eta_{PTC} = W_{net} / (G_b \cdot A) \tag{5}$$

The performance formula of a single PTC provided by the manufacturer is [11]:

$$\eta_{PTC}(T) = 0.762\kappa - 0.2125 \times (T - T_a) / G_b - 0.001672 \times (T - T_a)^2 / G_b \tag{6}$$

κ is incidence angle modifier and is expressed by

$$\kappa = \cos(\theta) + 0.0003178(\theta) - 0.00003985(\theta)^2 \tag{7}$$

3.2. Cost equations

The design thickness of the cylinder is correlated with the design pressure [12]

$$\delta_{cy} = pD_i / (2[\sigma]^t \phi - p) \tag{8}$$

Cylinder vessel generally has two elliptical heads at the top and the bottom. The standard ratio of the half long axis (a) and the half short axis (b) of an ellipse is 2:1. The design thickness is expressed by

$$\delta_{head} = pD_i / (2[\sigma]^t \phi - 0.5p) \tag{9}$$

Corrosion allowance shall be considered which will lead to higher cylinder and head thickness than those according to Eqs.(8) and (9).
The total mass of material used for a pressure vessel and the total cost are approximated by

$$M_{steel} = M_{steel,cy} + 2M_{steel,head} \tag{10}$$

$$C_{steel} = P_{steel} M_{steel} \tag{11}$$

The cost of PTCs is expressed by

$$C_{PTC} = P_{PTC} A_{PTC} \tag{12}$$

In this work, emphasis is put on the additional PTCs due to usage of LTA. The total heat released from HTA to LTA in the second stage of heat discharge is expressed by

$$Q = M_{water,LTA} \times (h_3 - h_4) \tag{13}$$

The additional PTCs are designed to provide such heat in the daytime and thus is calculated by

$$A_{PTC,LTA} = \frac{m(h_3 - h_4)}{G_{b,ref} \times \eta_{PTC}} \times \frac{t_{dur,ORC}}{t_{dur,ir,ref}} \tag{14}$$

where $t_{dur,ORC}$ is the operating time of the ORC in the second stage heat discharge; $G_{b,ref}$ and $t_{dur,ir,ref}$ are the reference solar beam radiation and daily duration.
The equivalent payback time (EPBT) is defined as

$$EPBT = (C_{LTA} + C_{PTC,LTA}) / (AP_{LTA}) \tag{15}$$

where C_{LTA} and $C_{PTC,LTA}$ are the cost of LTA and increased PTCs respectively; AP_{LTA} is the increased annual profit (AP).

4. Results and discussion

Some assumptions are made in the calculation as listed in Table 1. Subcritical cycles are considered for both ORC and SRC. The ORC turbine has a constant efficiency. The volumes of the HTA and LTA are both 275 m^3. The nominal hot side temperature of SRC (T_1) is 250 °C. In the first stage of heat discharge, the HTA has a temperature drop from 250 to 230 °C. According to the equations in Section 3, the estimated storage capacity is about 1.0 MWh_e in this stage.

Table 1. Specific parameters.

Term	Value	Term	Value
Minimum temperature difference, ΔT_{min}	5 °C	Accumulator Welding coefficient, Φ	0.8
Ambient temperature, T_a	25 °C	Accumulator Corrosion allowance,	5 mm
Peak isentropic efficiency of SE, $\varepsilon_{os,p}$	0.75	Gravity, g	9.8 m/s^2
Built-in volume ratio of SE, $r_{v,b}$	4.0	Reference solar radiation, $G_{b,ref}$	750 W/m^2
Turbine isentropic efficiency, ε_T	0.80	Reference daily irradiation duration, $t_{dur,ir,ref}$	6.5 hours
Generator efficiency, ε_g	0.95	Price of steel [13]	3600 RMB/ton
Pump efficiency, ε_P	0.80	Price of PTC [10]	1000 RMB/m^2
Nominal net electricity output, W_{net}	1 MW	Price of electricity [14]	1.15 RMB/kWh

4.1. Thermodynamic parameters on the optimum SORC power conversion conditions

Given the hot side and cold side temperature of the SORC, η_{SRC} decreases with the increment in the ORC evaporation temperature (T_{10}). Due to the trade-off between η_{SRC} and η_{ORC}, the cascade cycle efficiency is not a monotonic increasing function of the T_{10}. In general, η_{SORC} first increases when T_{10} goes up from the environment temperature, and reaches a maximum value. It then decreases with further increment in T_{10}. The optimum $T_{10,op}$ for the nine organic fluids are displayed in Table 2, which are referenced as the nominal operating parameters. Fluid of higher critical temperature usually has a higher $T_{10,op}$. The net electricity outputs of SRC and ORC (W_{SRC} and W_{ORC}) on the optimum conditions are also provided. The ratio of W_{SRC}/W_{ORC} is around 1:1, with highest and lowest values of 1.09 and 0.70 for isobutene and benzene, respectively. Unlike a solo SRC or ORC, the cascade cycle can offer a much higher heat-to-power conversion efficiency. The mass flows of SRC and ORC (m_{water} and m_{ORC}) on the nominal condition are 1.79 and 5.92 kg/s in case of benzene. And they are 1.83 and 5.64 kg/s, 1.87 and 15.86 kg/s, 1.89 and

6.83 kg/s, 1.91 and 12.80 kg/s, 1.91 and 15.20 kg/s, 1.92 and 7.99 kg/s, 1.92 and 4.53 kg/s in case of cyclohexane, R141b, R123, pentane, R365mfc, R245fa, butane and isobutene.

Table 2. Thermodynamic parameters on the optimum SORC conditions.

Working fluid	ORC evaporation temperature(°C)	ORC efficiency(%)	SRC efficiency(%)	SORC efficiency(%)	SRC electricity output(MW)	ORC electricity output(MW)
benzene	156	17.54	10.82	26.36	0.41	0.59
cyclohexane	152	16.39	11.14	25.61	0.43	0.57
R141b	150	15.96	11.29	25.36	0.45	0.55
R123	147	15.04	11.50	24.72	0.47	0.53
pentane	144	14.47	11.69	24.38	0.48	0.52
R365mfc	143	13.98	11.75	24.00	0.49	0.51
R245fa	137	13.36	12.06	23.74	0.51	0.49
butane	137	13.30	12.06	23.69	0.51	0.49
isobutene	133	12.89	12.24	23.49	0.52	0.48

4.2. Heat transfer from HTA to LTA

Given the volume of the accumulators, the total power that can be generated in the second stage of heat discharge (i.e. the increased storage capacity) is associated with the heat transfer from HTA to LTA, which is shown in Table 3. For each fluid, the ORC is able to work at nominal conditions. To complete the second stage discharge process, 11.0 to 15.7 hours of ORC operation are needed, depending on the fluids. Differing from 1.0 MWh_e storage capacity of a single accumulator, the storage capacity is increased appreciably by the LTA, in the range from about 6479 to 8390 kWh_e. Though benzene has the highest cycle efficiency, it produces the lowest electricity among the fluids. The reason is the relatively high temperature at the water outlet, as illustrated in Fig.2. The *T-Q* diagram is useful to reveal the relationship between fluid temperature and heat transfer in HX1. In the figure, all the organic fluids have condensation temperature of about 35°C. Water inlet temperature in all situations is 230°C. m_{ORC} is consistent with that on the nominal condition. However, m_{water} can be different from nominal values because in discharge process, water is just heat transfer media rather than expander fluid. To determine m_{water}, the minimum heat transfer difference (ΔT_{min}) should be known. For benzene, cyclohexane, R141b, R123 and pentane, ΔT_{min} occurs at the saturated liquid state (pinch point). For R245fa, butane, butane and isobutene, ΔT_{min} take places at the water outlet. Given the above parameters, m_{water} is available according to the law of conservation of energy.

Table 3. Increased storage capacity using different ORC fluids.

Working fluid	HTA temperature(°C)	LTA temperature(°C)	ORC operating duration/h	Water mass flow rate(kg/s)	Working fluid mass flow rate(kg/s)	Storage capacity(kWh_e)
benzene	230	108.80	10.99	6.32	5.92	6479.08
cyclohexane	230	90.03	12.31	5.64	6.20	6953.57
R141b	230	73.59	13.58	5.11	11.89	7534.89
R123	230	44.04	15.69	4.43	15.86	8390.44
pentane	230	41.51	15.71	4.42	6.83	8178.46
R365mfc	230	40	15.60	4.45	12.80	7962.68
R245fa	230	40	15.47	4.49	15.20	7609.54
butane	230	40	15.43	4.50	7.99	7575.37
isobutene	230	40	15.33	4.53	8.63	7341.84

The *T-Q* diagram is related to the characteristics of the fluids. Benzene is accompanied with the highest outlet water temperature attributed to the largest ORC evaporation temperature and latent heat. The ratio of specific latent heat of benzene in the evaporation process to the total energy in the heating process (i.e. h_{10}- h_{13}) is 58.2%. While it is 53.5%,49.3%,43.3%,44.4%,41.6%,35.1%,34.3%,33.5% respectively for cyclohexane, R141b, R123, pentane, R365mfc, R245fa, butane and isobutene. It means most of the heat is used for vaporization in case of benzene, resulting in the high operating temperature of water.

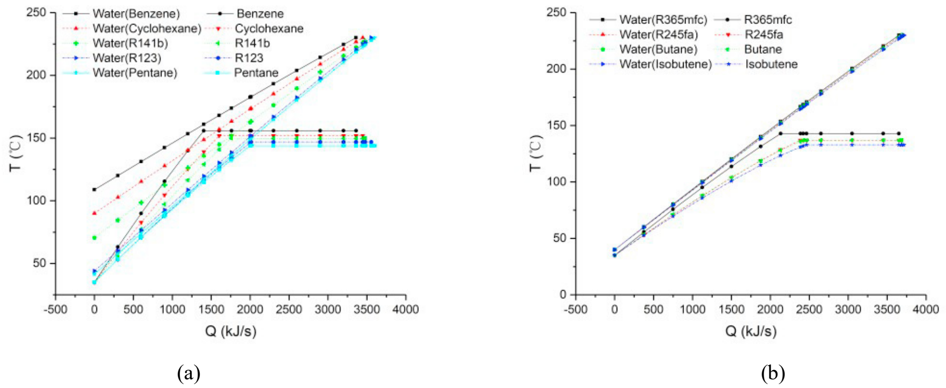

Fig.2. T-Q diagrams: (a) benzene, cyclohexane, R141b, R123, pentane; (b) R365mfc, R245fa, butane, isobutene

4.3. Cost estimation

In contrast to SEGS using a single-stage accumulator, the two-stage accumulators based system has investment on the LTA and the additional PTCs. As shown in Table 3, in most cases, the LTA operates at temperature lower than 100 °C and the accumulator cost should be low. The LTA for benzene-water application may have the highest technical requirement. Variation of wall thickness (δ_{cy}) and steel cost for the LTA with the diagram (D_i) of a horizontal accumulator is depicted in Fig.3, on the assumption of design temperature of 120 °C. δ_{cy} rises with the increment in D_i. On the other hand, the vessel length and surface area decrease. In view of the corrosion allowance of 5mm, the decrement in surface area has more significant effect on the steel mass and hence the cost falls down. At higher D_i, the corrosion allowance has less important influence on δ_{cy}. Further increment on D_i leads to steeper growth of δ_{cy}, larger head surface and more steel mass. The minimum material cost of LTA is around 72660 RMB when D_i=4670 mm. The corresponding δ_{cy} and the vessel height are about 9.30mm and 16.06m, respectively. Taking into account the manufacturing cost, a LTA cost of about 0.15 million RMB can be expected.

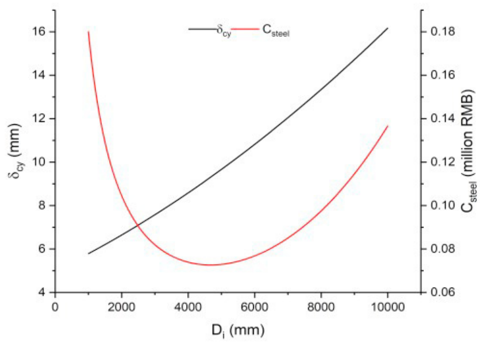

Fig.3. Variation of steel cost for the LTA

The expenditure for the additional PTCs is shown in Table 4. The PTC efficiency is determined by the inlet and outlet temperatures in the solar fields. The reference solar radiation ($G_{b,ref}$) is 750 W/m^2 and the reference daily irradiation duration ($t_{dur,ir,ref}$) is 6.5 hours. According to Eq.(14), the required solar collector area is proportional to the total heat released in the second stage discharge. Benzene offers the smallest PTC area, attributed to the lowest storage capacity. The largest cost is about 16.7893 million RMB with the fluids of R365mfc, R245fa, butane and isobutene, which is about 50% larger than that with benzene. The results also indicate that LTA plays a much less role than PTCs in the cost.

Table 4. Additional cost of SEGS using the two-stage accumulators.

Working fluid	PTC efficiency(%)	Required PTC area(m^2)	PTC cost(million RMB)	LTA cost(million RMB)	Total increased cost(million RMB)
benzene	66.51	11392.46	11.3925	0.1453	11.5378
cyclohexane	67.40	12911.39	12.9114	0.1453	13.0567
R141b	68.15	14209.80	14.2098	0.1453	14.3551
R123	69.42	16483.69	16.4837	0.1453	16.6290
pentane	69.53	16675.14	16.6751	0.1453	16.8204
R365mfc	69.59	16789.28	16.7893	0.1453	16.9346
R245fa	69.59	16789.28	16.7893	0.1453	16.9346
butane	69.59	16789.28	16.7893	0.1453	16.9346
isobutene	69.59	16789.28	16.7893	0.1453	16.9346

4.4. Payback time

Typical meteorology year isolation data for Phoenix, Lhasa, Sacramento, Cape Town, Canberra, Delingha, Dunhuang are exemplified. The daily isolation duration with direct beam radiation stronger than 500 W/m^2 in these areas is about 7.7, 6.8, 6.0, 5.7, 4.9, 3.6 and 4.4 hours, respectively. The equivalent payback time (EPBT) is presented in Table 5. Notably, given the working fluid and region, EPBT is a very weak function with the PTC area under the consideration of insignificant LTA cost. More PTCs lead to almost linearly increased collector investment as well as annual electricity yield. Therefore, the ratio of the investment to the yield remains unvaried. For different fluids and regions, EPBT ranges from 3.68 to 9.92. In view of the much longer payback time of conventional SEGSs (12 years or more), the usage of LTA has great potential to improve the system's cost-effectiveness.

The shortest payback time is achieved when using benzene of the highest solar thermal electricity efficiency. However, it doesn't necessarily result in the most economical benefits to the whole system. Due to the lowest heat storage capacity with benzene, the influence of the increased PTCs on the total cost of the SEGS may be least appreciable. The weighting factor of EPBT in the system cost varies with the working fluids.

Table 5. Equivalent payback time in six areas, unit: year.

Working fluid	Phoenix	Lhasa	Sacramento	Cape Town	Canberra	Delingha	Dunhuang
benzene	3.68	4.80	4.80	5.03	5.63	8.11	7.94
cyclohexane	3.86	5.01	5.03	5.26	5.88	8.36	8.29
R141b	3.90	5.05	5.07	5.30	5.91	8.33	8.33
R123	4.03	5.19	5.21	5.45	6.07	8.39	8.54
pentane	4.18	5.38	5.41	5.65	6.29	8.69	8.85
R365mfc	4.32	5.56	5.59	5.83	6.50	8.97	9.15
R245fa	4.52	5.82	5.85	6.10	6.80	9.39	9.57
butane	4.54	5.84	5.87	6.13	6.83	9.43	9.62
isobutene	4.69	6.03	6.06	6.33	7.05	9.73	9.92

4.5. Further discussion

Some systems related to the one in this paper have been investigated previously. Owing to the elimination of superheater, DSG-SEGS using steam SE and cascade steam-organic Rankine cycle has similar efficiency with conventional CSP system (e.g. SEGS I in 1984),while the operating temperature can be much lower [1].Water that acts as heat collection, storage and SE working fluid offers thermodynamic and economic advantages [2]. The proposed DSG-SEGS characterized by two-stage accumulators is an improvement of the aforementioned systems. A brief comparison between the novel system and SEGS I can be made. The former is more efficient and free of thermal oil, but has additional investment on the steam SE. According to Jiangxi Huadian Electrical Power Co.,Ltd. and Zhejiang Kaishan Compressor Co.,Ltd., current cost of a 1 MW SE is around 4 million RMB. In SEGS I, the oil temperature drop from the hot to the cold tank was about 67 °C and the design storage capacity was 2.5 hours. It can be deduced that if the system is rescaled to 2 MW (1MW SE+1MW turbine), 488 tons of thermal oil will be required. With 18500 RMB per ton [2], the oil cost should be 9.03 million RMB, which remarkably exceeds the expander cost. Notably, the market for SE is booming and lower cost of this kind of expander is expected in the near future. In consideration of the high storage capacity, the novel system shall have a shorter payback time than SEGS I.

There is great uncertainty on land cost and is not taken into account in the analysis. For PTC with an aperture length of 5.8 m, the distance between neighbouring rows may be 18 m. 53 to 78 acres of lands may be required in accordance with collector area of 11392 to 16789 m^2. The land cost is supposed to be less than 20% of the PTC's.

Finally, 1000 RMB/m^2 is the current market price of PTCs in China, and the PTCs are supposed to be applied in conventional CSP system operating at temperature higher than 400 °C. The PTCs in the novel system work around 250 °C, and therefore the technical requirement is lower and the collectors could be cheaper.

5. Conclusion

In principle, the two-stage accumulators differ from existing solar thermal storage technologies. The HTA first experiences a mass-unvaried heat discharge process, and then undergoes an isothermal process. The two-stage accumulators combine the advantages of conventional single-stage accumulator and two-tank storage system. They are a perfect match to the cascade steam-organic Rankine cycle.

By enlarging the temperature drop of water during heat discharge, the storage capacity of the system can be increased from 1MWh_e with single-stage accumulator to 8.4 MWh_e with LTA. Meanwhile, highly off-design operation of the SRC is avoided and the ORC is able to work steadily, especially during the second stage of heat discharge.

The equivalent payback period related to the LTA and additional PTCs is about 5 years in areas of rich solar resource such as phoenix and Lhasa. Shorter payback period is expected when the PTCs are mass-produced in the future.

6. Future work

Thermo-economic performance of the whole system will be investigated in consideration of investments on the screw expander, solar field, high temperature accumulator, etc. The annual yield of the system in different areas will be analysed. Comprehensive comparison between the innovative system and the mainstream SEGS will be conducted.

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