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Optimization of parabolic trough solar collectors integrated with two stage Rankine cycle

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A B S T R A C T

In this paper, detailed exergy and energy analysis of selected thermal power systems driven by parabolic trough solar collectors is presented. solar energy is used to feed a two stage steam Rankine cycle to supply domestic hot water. To determine the irreversibilities in each component and assess the system performance, a parametric study is performed to investigate the effects of varying design parameters and operating conditions such as the effects of the ambient temperature, solar radiation, and high pressure turbine pressure ratio and solar cycle mass flow rate, on the system energy and exergy efficiencies. An optimization with an evolutionary algorithm is applied to determine the best exergetic performance. This study reveals that the main source of exergy destruction is the solar collector where contributes more than 45% of total exergy destruction. In addition, heater, condenser and heat exchanger contribute to 16%, 15% and 14%, respectively. Finally, this study reveals that optimization using genetic algorithm improves the exergy efficiencies up to 58.03%.

1. Introduction

Today, Energy has an important role in our communities. With increases population, world energy demand is increasing steadily. Fossil fuel reserves are limited and Burning fossil fuels results in the release of large amounts of greenhouse gases, such as carbon dioxide [1]. Greenhouse gases emission is the major problem for developed countries, there for using non-conventional fuels and renewable energy instead of fossil fuels is proposed as alternative energy sources. Renewable energy sources are solar, biomass, hydro, wind, wave, tidal, ocean current, ocean thermal, and geothermal [2]. Ozturk and dincer [3] have investigated solar energy applications such as electricity generation, heating, and cooling. Al-Sulaiman et al. [4] carried out energy and exergy analyses of an organic Rankine cycle (ORC) driven by biomass. ORC is one of the low-temperature cycles in which water is used as the working fluid. Solar energy is an environmentally benign energy source, as pointed out by Khalid et al.[5] and Al-Ali and dincer [6]. Ahmadi et al. [7] performed energy and exergy analyses and an environmental impact assessment for a multi generation system that consists of micro gas turbine, a dual pressure heat recovery steam generator. Parabolic trough solar collector (PTSC) technology is propounded the most established solar thermal technology for power production. This technology To collect solar energy has been selected for this study. Quoilin et al. [8] carried out thermodynamic modeling of a proposed small scale PTSC integrated with an ORC for power production. the performance of a low temperature solar thermal electric system using an ORC and a compound parabolic trough was proposed by Gang et al. [9]. It was shown that the overall electrical efficiency was about 8.6% when a solar irradiation of 750 W/m2 was assumed. Al-Sulaiman [10] conducted an energy analysis of PTSC integrated with a steam Rankine cycle as a topping cycle and an ORC as a bottoming cycle. His study considered the energetic performance of his system and the effect of selected parameters on the size of the solar collector field. Al-Sulaiman [11] although performed energy and exergy analysis of parabolic trough solar collectors integrated with combined steam and organic Rankine cycles.

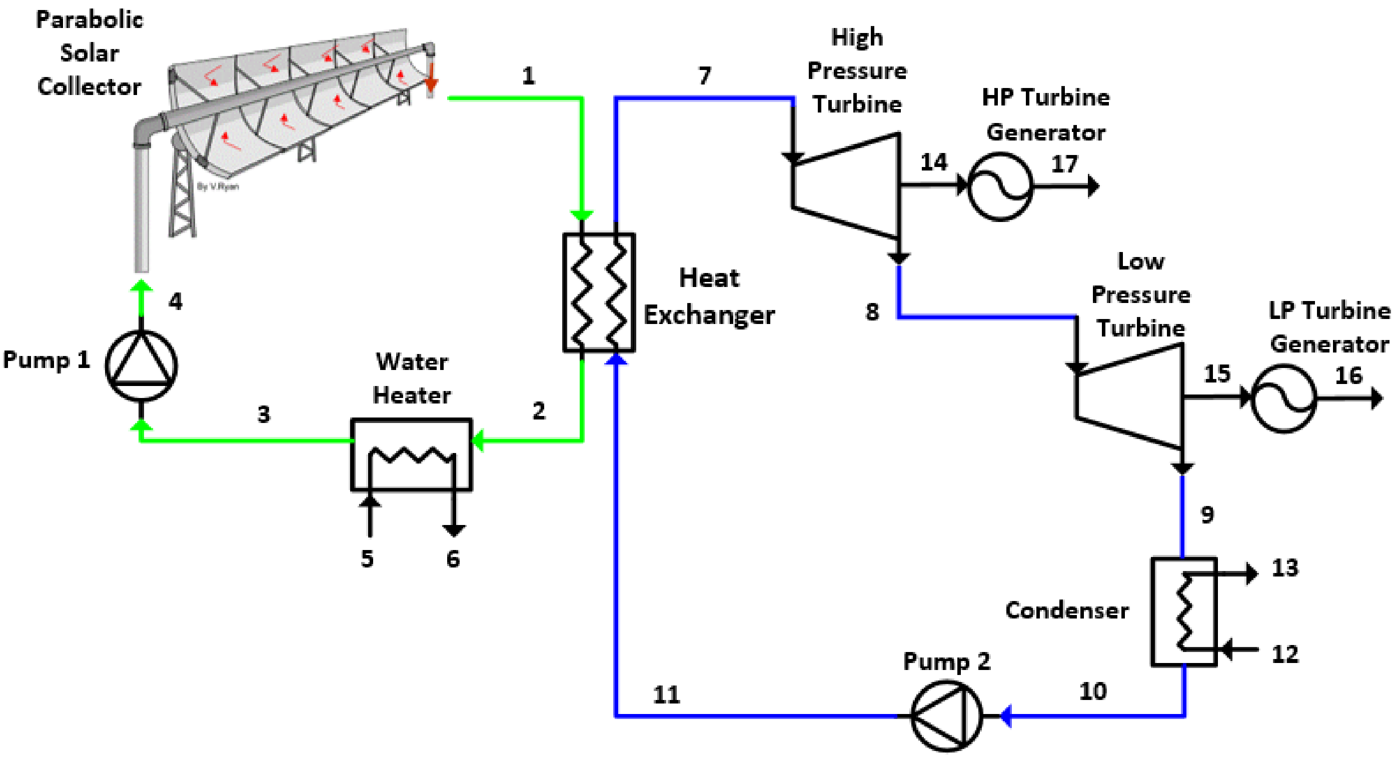

Figure1. Schematic of the proposed system

The objective of the current study is to examine, in detail, energy and exergy efficiencies as the thermodynamic performance of a power generation system driven by parabolic trough solar collectors that are integrated with a double-stage steam turbine in Rankine cycles. In this study, key exergetic parameters are examined: exergetic efficiency and exergy destruction rate. Sensitivity analysis is carried out in order to observe the effect the design parameters on the system performance Thermodynamic analysis of the cycle has been implemented based on engineering equation solver software (EES). Data brought in this paper have been utilized in Khuzestan Province, Iran. This province is among the most prone areas in Iran in the exploitation of solar energy having had over 300 sunny days.

2. Materials and Methods

System description

The current study is configured to make use of heat energy in two-stage steam Rankine cycles and the waste heat of the PTC cycle is utilized in the water heater. Solar energy is collected by a parabolic trough solar collector.

In PTC cycle hot temperature working fluid at point 1 goes to the heat exchanger to heat the water in the two stage steam Rankine cycle. The rest of the heat energy passes through water heater at point 2 to heat the domestic water then the working fluid pumps into solar collector by pump 1 at point 3. Heated steam in the heat exchanger is expanded in the high-pressure turbine at point 7 to produce work. Waste heat from the high-pressure turbine expands in the low-pressure turbine at point 8 to produce more work. Two-stages are used, to increase efficiency and use the waste heat, to produce more electricity. At point 9 the steam exiting from the second turbine is then condensed and then pumps into heat exchanger at point 10 and cycle will be complete.

Mathematical modelling

Mathematical modeling of the systems considered is presented in this section. The equations developed were programmed using Engineering Equation Solver (EES). Modeling the solar-cogeneration system is presented first. Then the exergy analysis of the overall system is presented. For simplifying the theoretical analysis, following assumptions are made:

- All processes reach a steady state.
- Pressure losses in pipes are negligible.
- the isentropic efficiencies of pumps and turbine are known.
- all of the potential and kinetic energies are neglected.

Energy analysis

In the analysis of the system, the conservation laws of mass, momentum, energy and their corresponding assumptions are used which were mentioned above. Each component in the system can be treated as a control volume. For a control volume with inlet i and outlet e, mass and energy conversation are as below:

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

$$\sum \dot{Q} - \sum \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \tag{2}$$

The conservation of mass and energy principle applied to each component can be expressed as follows:

- Domestic water heater

The energy balance for this component is given as follow

$$\dot{m}_{sc}(h_2 - h_3) = \dot{m}_{dwh}(h_6 - h_5) \tag{3}$$

- Heat exchanger

The energy balance for heat exchanger is defined as following

$$\dot{m}_{sc}(h_1 - h_2) = \dot{m}_{st}(h_7 - h_{11}) \tag{4}$$

- Pump 1

The power consumed by pump 1 is expressed as

$$\dot{W}_{p,sc} = \dot{m}_{sc} v_3 (P_4 - P_3) / \eta_{is,p1} \tag{5}$$

- Two stage steam Rankine cycle

The power that can be obtained from the high-pressure turbine of two-stage steam Rankine cycle is defined as

$$\dot{W}_{hp} = \dot{m}_{st}(h_7 - h_8) \tag{6}$$

Here, the power obtained from the low-pressure turbine is:

$$\dot{W}_{lp} = \dot{m}_{st}(h_8 - h_9) \tag{7}$$

And energy efficiency of turbine is defined as

$$\eta_{is,Turb} = \frac{\dot{W}_{Turb}}{\dot{W}_{is,Turb}} \tag{8}$$

- Condenser

The rate of heat rejected by the condenser is defined as

$$\dot{Q}_{cond} = \dot{m}_{st}(h_5 - h_1) \tag{9}$$

- Pump 2

The power consumed by pump 2 is expressed as

$$\dot{W}_{p,st} = \dot{m}_{st} v_{10} (P_{11} - P_{10}) / \eta_{is,p2} \tag{10}$$

- Solar Collector

$$\dot{m}_1 = \dot{m}_4 \tag{11}$$

$$\dot{Q}_{Solar,Co} = \dot{m}_1 (h_1 - h_4) \tag{12}$$

Exergy analysis

Exergy is the maximum work that can be obtained from a given form of energy using the environmental parameters [12]. The total exergy of a system X can be divided into four components: physical exergy X_{PH}, kinetic exergy X_{KN}, potential exergy X_{PT} and chemical exergy X_{CH} [13].
In this study, the kinetic and potential exergy are assumed to be negligible as the elevation and speed have negligible changes [13]. Applying the first and the second law of thermodynamics, the following exergy balance is obtained [14]:

$$\dot{X}_Q + \sum \dot{m}_i x_i = \sum \dot{m}_e x_e + \dot{X}_W + \dot{X}_D \tag{13}$$

$$\dot{X}_Q = \left(1 - \frac{T_0}{T}\right)\dot{Q} \tag{14}$$

$$\dot{X}_W = \dot{W} \tag{15}$$

Where X_Q and where X_W is the corresponding exergy of heat transfer and work which across the boundaries of the control volume. The exergy destruction rate for each component for the whole system is shown in Table 1.

Table 1. Exergy destruction rate of components of system

Component	Exergy destruction rate
HP Turbine	$\dot{X}_{d,HPT} = \dot{m}_7(x_7 - x_8) - \dot{W}_{HP}$
LP Turbine	$\dot{X}_{d,LPT} = \dot{m}_8(x_8 - x_9) - \dot{W}_{LP}$
Condenser	$\dot{X}_{d,Cond} = \dot{m}_9 x_9 + \dot{m}_{12} x_{12} - \dot{m}_{10} x_{10} - \dot{m}_{13} x_{13}$
Heat exchanger	$\dot{X}_{d,HX} = \dot{m}_1 x_1 + \dot{m}_{11} x_{11} - \dot{m}_2 x_2 - \dot{m}_7 x_7$
Pump 2	$\dot{X}_{d,P2} = \dot{W}_{P2} + \dot{m}_{10} x_{10} - \dot{m}_{11} x_{11}$
Pump 1	$\dot{X}_{d,P1} = \dot{W}_{P1} + \dot{m}_1 x_1 - \dot{m}_2 x_2$
Water Heater	$\dot{X}_{d,WH} = \dot{m}_2 x_2 + \dot{m}_5 x_5 - \dot{m}_3 x_3 - \dot{m}_6 x_6$
HP Generator	$\dot{X}_{d,GEN} = \dot{X}_{14} - \dot{X}_{17}$
LP Generator	$\dot{X}_{d,GEN} = \dot{X}_{15} - \dot{X}_{16}$
PTC	$\dot{X}_{d,PTC} = \left(1 - \frac{T_0}{T}\right)\dot{Q}_{Solar} + \dot{m}_4(x_4 - x_1)$

Table 2. Results of simulation for the CHP system.

State	T(C)	P(KPa)	m(Kg/s)	Ex(kW)
0	25	101.3		
1	261.9	21000	0.4	445.7
2	275	17000	0.4	161.6
3	200	17000	0.4	92.96
4	200	17000	0.4	314.3
5	25	150	0.31	0.049
6	75	150	0.31	15.94
7	251.9	2000	0.1	958.2
8	107.9	103.3	0.1	485.4
9	78.43	44.44	0.1	326.5
10	78.43	44.44	0.1	17.97
11	78.74	2000	0.1	20.11

12	15	150	0.99	0.745
13	66.16	150	0.99	11.02

3. Results and Discussion

In this section, the results of exergy modeling of the cogeneration system using solar energy are presented and discussed. In this study, the effects of the ambient temperature, solar radiation, and high-pressure turbine pressure ratio and solar cycle mass flow rate are examined. In the calculations, the mass flow rate of the water in steam Rankine cycle is kept constant for each operating. Table 2 shows the thermodynamic state of the CCHP system driven by solar energy, and Table 3 shows the results of the thermodynamic simulation.

Table 3. The performance of the proposed CHP system.

Turbines power (kW)	49.64
Heating power (kW)	65.04
Thermal efficiency (%)	78.12
Exergy efficiency (%)	46.25

Exergy destruction rates for main components of the system are shown in figure 2 Each component is considered as a control volume and exergy input and outputs from this control volume are calculated to find exergy destruction. The comparison of exergy destruction is a way to compare irreversibilities in different parts of the system.

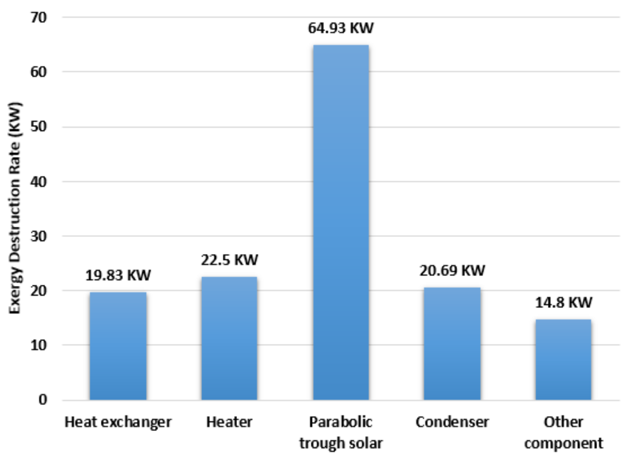

Figure 2. Exergy destruction rates for main components of system

The highest destruction in CHP system is in parabolic trough solar or PTC. Then comes the heater, the condenser and heat exchanger respectively. In the solar collector, the irreversibility created is due to large temperature difference between solar heat and fluid in the tubes. Therefore, in designing a solar-cogeneration system, the most significant components that require careful design and selection are the solar collectors and heat exchangers.

The parametric analysis is achieved to evaluate the effects of each key parameter (as mentioned above) on the system performance in the CHP system. In the parametric analysis, where one parameter is varied, the other parameters are kept constant.

Both system energy and exergy efficiencies increase with increasing ambient temperature as shown in Figure 3 the rate of increase is the same for both graphs. The efficiencies increase because the increase in the system outputs (as a result of ambient temperature) is more noticeable than the increase of the system inputs.

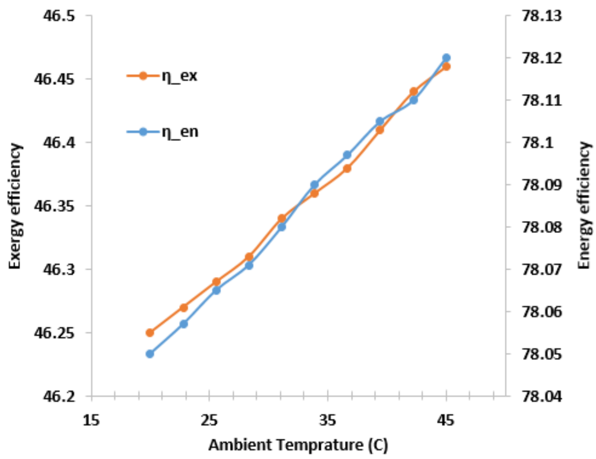

Figure 3. Effect of ambient temperature on system performance

Solar radiation is directly proportional to system energy and exergy efficiencies as Figure 4 shows. The energy efficiency curve is parabolic and is pointing up. The reason that the rate of increase of energy efficiency is more than the rate of increase of exergy efficiency is because the exergy increase of the system (by the increase in solar radiation) is much more than the increase in the system exergy outputs. For system energy outputs, the rate of increase dominates as solar radiation increases.

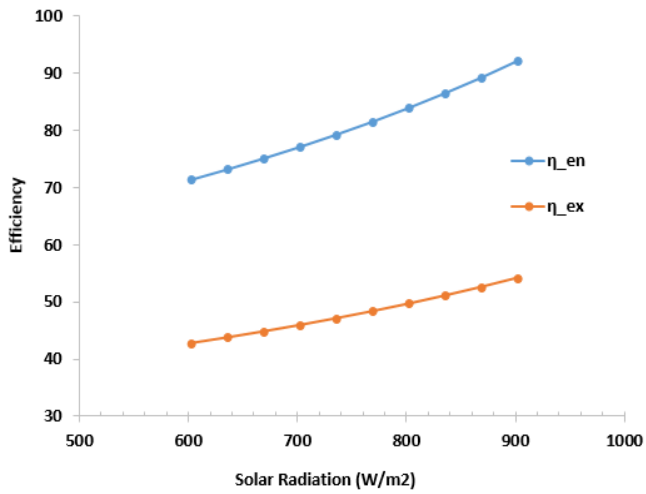

Figure 4. Effect of solar radiation on system performance

High-pressure turbine pressure ratio significantly affects system performance like energy and exergy efficiencies. Figure 5 shows the variation with compressor pressure ratio of energy and exergy efficiencies, for the CHP system. As illustrated in the figure, both energy and exergy efficiencies increase with increasing the HP turbine pressure ratio mainly due to an increase of HP turbine output work. Although LP turbine output work decrease with increasing of the HP turbine pressure ratio but increase the rate of HP output work is much more that can compensate the reduction.

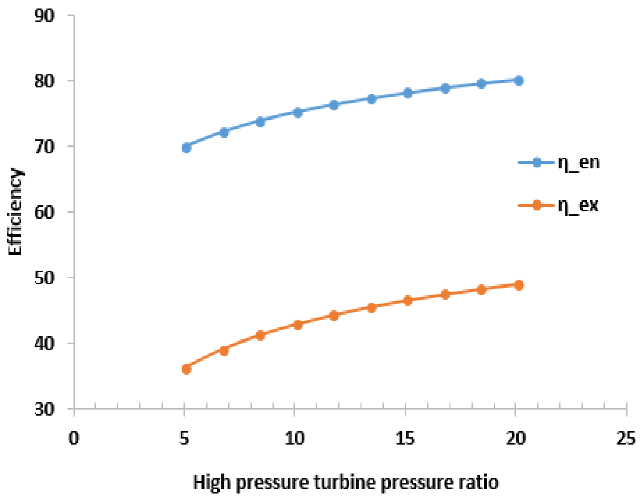

Figure 5. Effect of high-pressure turbine pressure ratio on system performance

It is clear in figure 6 solar cycle mass flow rate has a positive effect on system performance. The reason is an increase of the heating power in the heater. It is observed that the temperature at state 7 decreases with the increase of the Therminol_VP1 mass flow rate. This is due to temperature reduction of the solar cycle flow at the outlet of the PTC. It is obvious the result of temperature reduction at the inlet of HP turbine is decrease of the output power of both HP and LP turbines, however, the increase rate of heating power in the heater can offset the reduction and raise system performance.

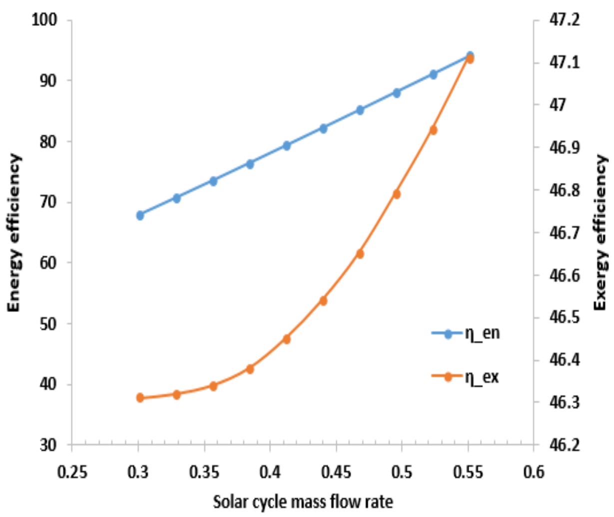

Figure 6. Effect of solar cycle mass flow ratio on system performance

Optimization of System is performed in Engineering Equation Solver based on Genetic algorithms. For the purposes of optimizing parameters, all independent variables that have an effect on the results are chosen first, then their minimum, maximum bounds and guess values are determined and the minimum or maximum value is reached. Genetic algorithms apply an iterative, stochastic search strategy to find an optimal solution and imitate in a simplified manner principles of biological evolution [93]. The results in table 4 are obtained for maximum exergy efficiency of the system.

Table 4. The optimization result of the CHP system.

Ambient temperature (^{o}C)	25.18
Solar radiation (W/m^2)	857.4
HP turbine pressure ratio	19.9
Solar cycle mass flow rate (Kg/s)	0.5439
Exergy efficiency (%)	58.03

If the system exergy efficiency is desired to be maximized, the variable values and the final results in table 3 are obtained. Maximum system exergy efficiency is 58% when solar radiation is 857.4 W/m^2, the solar system fluid mass flow rate is 0.5439 kg/s, pressure ratio on the HP turbine is 19.9 and the ambient temperature is 25.18°C.

4. Conclusions

In this study, a solar CHP system in Khuzestan province's situation is proposed and Energy and exergy analysis of this system are conducted. Moreover, overall exergy destruction rate of the system and each component is calculated. The performance of system is examined by varying key parameters such as ambient temperature, solar radiation, HP turbine pressure ratio and solar cycle mass flow rate. The following remarks can be concluded from this study:

- Energy and exergy efficiency of the solar CHP system is 78.12% and 46.25%, respectively. It is clear that system operates efficiently in Ahvaz situation.
- The solar collector is the main exergy destruction that destroys 45% of the total destructed exergy. Heater, condenser and heat exchanger contribute to 16%, 15%, and 14%, respectively. Thus, for increasing system exergetic performance it is essential to have the careful design of these components. Other components have lower exergy destruction rates in comparison to these two components.
- An increase in ambient temperature, solar radiation, HP pressure ratio and solar cycle mass flow rate has a positive effect on solar-cogeneration system performance.
- Optimization of the solar-cogeneration system using GA improves the exergy efficiencies up to 58.03%.

List of symbols

E	Modulus of elasticity
k	Stiffness
p	Acoustical pressure
p_0	Amplitude of the excitation plane wave

p_b	Blocked pressure

Greek symbols (Optional)

σ	Flow resistivity
τ	Tortuosity

Subscripts

SC	Solar cycle
dmh	Domestic water heater
st	Steam turbines
p	pump
hp	High pressure
Lp	Low pressure
is	isentropic
turb	turbine
cond	condenser
hpt	High pressure turbine
lpt	Low pressure turbine
hx	Heat exchanger
wh	Water heater

Abbreviation

CHP	Combined Heat and Power
EES	Engineering Equation Solver
GA	Genetic Algorithm
HP	High Pressure
LP	Low Pressure
ORC	Organic Rankine Cycle
PTC	Parabolic Trough Collector

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