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Research Article

Thermo-economic feasibility analysis of trilateral-cycle power generators for waste heat recovery-to-power applications

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ABSTRACT

The trilateral cycle (TLC), a promising alternative waste heat recovery-to-power cycle, is receiving increasing attention due to feats such as the high thermal match between the exergy of the heat source temperature profiles and its working fluid. Although the TLC has neither been broadly applied nor commercialised because of its thermo-economic feasibility considerations. This study examined the thermo-economic analysis of different TLC power generator configurations; i.e., the saturated subcritical simple (non-recuperative) and recuperative cycles using *n*-pentane as the working fluid for low-grade waste heat recovery-to-power generation. Based on the thermodynamic and economic analyses, the feasibility analysis models of the cycles were established using Aspen Plus, considering efficiency, cost, and expected operating and capacity factors. Furthermore, the capacity factor, specific investment cost (SIC), and payback period (PBP), among other, were used to evaluate the cycle design configurations and sizes. The SICs of the simple and recuperative TLCs were 3,683.88 $/kW and 4,220.41 $/kW, and their PBPs were 8.43 years and 8.55 years, respectively. The simple TLC had a lower investment ratio of 0.24 compared to an investment ratio of 0.28 for the recuperative TLC. These economic values suggest that the simple TLC is more cost-effective when compared with the recuperative TLC because the recuperation process does not recompense the associated cost, making it unattractive.

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INTRODUCTION

The combination of growing environmental considerations, the necessity to increase the efficiency of conventional energy systems, and the need to close the energy demand and supply gaps has increasingly accelerated the global energy transition to incorporate alternative and low-carbon power technologies such as hydropower, solar thermal, biomass, and waste heat recovery [1–9]. Moreover, applications of waste heat recovery-to-power such as those

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for electricity generation have become a paradigm shift in advancing power generation systems for efficiency benefits and reductions in fuel demand, pollutants, and greenhouse gas emissions [3,10,11]. Consequently, a great deal of advanced (modified) Rankine cycles have been technologically and creatively utilised [3,5,6]. Among these, the trilateral cycle (TLC), also referred to as the trilateral flash cycle or the trilateral wet vapour cycle, is a viable heat recovery to power cycle [3]. The TLC is advantageous for low-to-medium temperature heat recovery-to-power applications because of its high performance at relatively low compression work [3,5], in particular, from non-isothermal heat sources [12]; the thermal match between the exergy of the heat source temperature profiles and the working fluid [3,5]; and moderate operating pressures so that its usage is economically feasible to generate shaft work for power generation or other applications [5,13].

A number of thermo-techno-economic feasibility studies on novel power cycles for heat recovery-to-power applications have been carried out. McGinty et al. [14] conducted a techno-economic feasibility survey of a pilot TLC power generator test rig in a steel production plant. They investigated three diverse heat sources and reported an expected annual power recovery of 782 MWh from these heat sources. Yari et al. [15] carried out an exergoeconomic assessment of the TLC, ORC, and Kalina cycle for low-grade waste heat recovery. They reported that a rise in the TLC's expander inlet temperature led to a rise in its net work output and a reduction in the product cost of the TLC power generator, which differed from the ORC system. Though the TLC can attain a higher net work output when compared with the ORC and Kalina cycle power generator systems, its cost of components was significantly influenced by the isentropic efficiency of the expander. Lecompte et al. [16] carried out a thermo-economic comparison of optimised ORC, transcritical Rankine cycle and TLC at 100°C to 300°C temperature range. They reported that the thermo-economic of the cycles was promising, in particular, the TLC. Though the costs of the initial investment for the considered transcritical Rankine cycle and TLC were often higher than the ORC for similar net work output.

Despite the TLC's promising thermodynamic, technical, and cost performances when compared to ORC and other advanced Rankine cycles, a review of the relevant literature revealed knowledge gaps regarding the potential advantages of the various TLC configurations from thermo-techno-economic perspectives [17]. Furthermore, for a wider spread of resource exploitation, knowledge, specific policy and governance supports, critical strategic issues of cost benefit analysis (costs for the system, operation and maintenance), payback time and most of all the perceived technical risks of the TLCs must be considered to enable their development for commercialisation. Thus, this paper presents the thermo-economic analysis of a variety of TLC power generator configurations (saturated subcritical simple (non-recuperative) and recuperative cycles), operating with n-pentane as the working fluid for low-grade waste heat recovery-to-power generation.

METHODOLOGY

For low-grade waste heat recovery-to-power generation, the thermo-economic analysis of a variety of saturated subcritical simple (non-recuperative) and recuperative trilateral-cycle (TLC) power generator configurations using n-pentane as the working fluid was conducted, taking into account the components and ancillary equipment, the energy input investment costs, as well as the operation and maintenance costs. From published literature, primary information on the technical, thermodynamic, and economic components was acquired. The Aspen Process Economic Analyzer® was used to create and apply the thermo-economic process models. Based on their thermo-economic performances, two distinct TLC configurations – the simple and recuperative TLC power generation systems – were taken into consideration. The following variables were calculated and analysed in this study: specific investment costs (SIC), investment ratio, profitability index, internal rate of return (IRR), net present value (NPV), and payback period (PBP).

System Description

The simple TLC consists of four key components, which are feed pump, heater, two-phase expander and condenser; and four basic thermodynamic processes. These thermodynamic processes include the isentropic compression of the working fluid by the feed pump (processes 1 to 2); the addition of high-temperature heat at constant pressure by the heater (processes 2 to 3); the expansion of high-pressurised heated working fluid by the expander (processes 3 to 4); and the rejection of working fluid low-temperature heat in the condenser (process 4 to 1). The high-pressurized and heated fluid is fed into the expander, where shaft work is produced to power an electric generator, in a manner

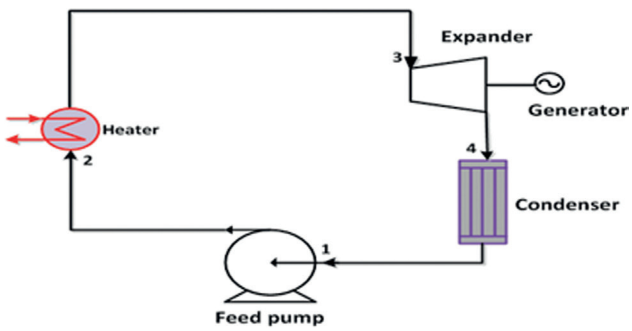


Figure 1. The simple trilateral-cycle configuration.

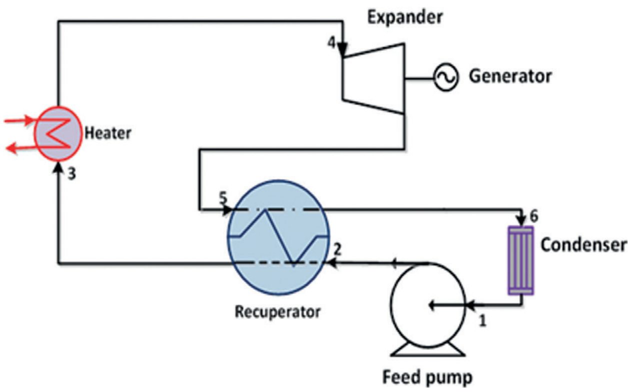


Figure 2. The recuperative trilateral-cycle configuration.

similar to the Rankine cycles. The subsequent condensation of the produced vapour-liquid content initiates a new cycle. Figure 1 depicts the simple TLC configuration, indicating its key components.

The recuperative TLC consists of five key components, namely the feed pump, recuperator, heater, two-phase expander, and condenser, as well as five basic processes, one of which is the latent heat recovery at the expander exhaust in addition to the simple TLC processes (process 5 and 2). The recuperator, an internal heat exchanger (IHE), is an addition that distinguishes the recuperative TLC from the simple TLC that does not use a recuperator but instead bleeds the latent heat at the expander exhaust. In contrast to the simple TLC, the recuperator at the expander outlet bleeds the working fluid's latent heat, which is then used to pre-heat the high-pressurised sub-cooled liquid at the pump output following the expander's flash expansion. Figure 2 depicts the recuperative TLC configuration, indicating its key components.

Thermo-economic Analysis

The feed pump, expander, and the generator sizing and costing for each cycle were based on their power output or consumption, which were also utilised as the component capacity index in the cost estimation. Likewise, each heat exchange equipment, which includes the heater, condenser and IHE were sized based on the total heat exchange area. The total heat exchange area is the sum of heat exchange areas for all its zones. Hence, the total heat exchange rate, HXR_T to or from the working fluid can be expressed using Eqn. (1) [18]:

$$HXR_T = \frac{\dot{Q}_{in}^{hx}}{U \times F_T \times \Delta T_{lm}} \quad (1)$$

Where $\dot{Q}_{in}^{hx}$ is the rate of heat input to the heat exchanger, ΔTlm is the logarithmic mean temperature difference

Table 1. Cost coefficients and correlations for components cost estimation of the simple and recuperative TLC power generator systems

Component	***A***	F_T	K_1	K_2	K_3
Pump	$\dot{W}_p(hp)$	2.7	9.0073	0.4636	0.0519
Expander	$\dot{W}_{ex}(kW)$	1	2.2476	1.4965	-0.1618
Generator	kW	$C_B = 1{,}850{,}000 \times \left(\frac{P}{11{,}000}\right)$			

P is the generator power output

Source: [20]; [21])

Table 2. The component size factors of the simple and recuperative TLC power generator systems

Component	***A***	F_T	C_0	C_1	C_2
Heater	HTA (m^2)	1	10.106	-0.4429	0.0901
Condenser	HTA (m^2)	1	9.5638	0.5320	-0.0002

Source: [18]; [19])

between the shell (hot) side and the tube (cold) side, F_T is the correction factor, and U is total heat exchange coefficient obtained from the heat transfer design coefficients for the working fluid of the heat exchanger. The logarithmic mean temperature difference, ΔT_{lm} can be computed using Eqn. (2) [18]:

$$\Delta T_{lm} = \frac{(T_{hs,i+1} - T_{cs,i}) - (T_{hs,i} - T_{cs,i-1})}{In((T_{hs,i+1} - T_{cs,i})/(T_{hs,i} - T_{cs,i-1}))} \quad (2)$$

To obtain the logarithmic mean temperature difference (ΔT_{lm}), the varying temperature for the hot side (Ths) and cold side (Tcs) of the TLC power systems temperature data were used. The size of the feed pump, S_{fp} can be expressed using Eqn. (3) [19]:

$$S_{fp} = \dot{V}\sqrt{H} \quad (3)$$

Where $\dot{V}$ is the volumetric flow-rate and H is the pump head. The size of the expander S_{exp} can be determined using the expander power rating for the power output as the working fluid is expanded [19,20]. Tables 1 and 2 present the cost coefficients and component size factors correlations used to estimate the component cost of the simple and recuperative TLC power generator systems. The correlations for component-based costs (indexed in the year 2013) as contained in Chemical Engineering Plant Cost Index (CEPCI) was employed for component sizing and costing [21]. For up-to-date component-based costs, year-to-year conversion variations were introduced with the logarithmic correlations of component size factors (A) with cost index CEPCI2019 = 607.5.

Evaluation of Thermodynamic Parameters and Investment Cost of System Components

The thermodynamic properties and costs of the mentioned system components were used in this study to evaluate the investment cost. The established component cost correlations for common industrial equipment were used to estimate the costs of the essential components [22]. Established correlations for conventional equipment were used to estimate the component-based prices because there was little information available, if any, about the actual component costs of the TLC systems. The component-based costs were evaluated using the TLC power generation systems' thermodynamic properties. The established logarithmic correlation of the component size factors was used to determine the expander's component-based cost. This component-based cost can be expressed using Eqn. (4) [21]:

$$\mathrm{Log}_{10} C_B = K_1 + K_2 \,\mathrm{Log}_{10}\,(A) + K_3\,[\mathrm{Log}_{10}\,(A)]^2 \qquad (4)$$

Where C_B is the component-based costs, A is the component attribute and K1, K2 and K3 are the determined cost coefficients for the equipment types. The component-based cost for feed pump, heater and condenser was estimated using the exponential correlation of the component size factors. This component-based cost can be expressed using Eqn. (5) [19]:

$$C_B = exp\{C_0 + C_1\,[\ln A] + C_2[\ln A]^2\} \qquad (5)$$

Where C_0, C_1 and C_2 are the cost coefficients, A is the component attribute (or size factors). When the capacity of the to-be-estimated component differs from those of known costs, the cost of the component was estimated using the correlation in Eqn. (6) [21]:

$$\frac{C_a}{C_b} = \left(\frac{A_a}{A_b}\right)^n \qquad (6)$$

Where C_a and A_a are the equipment cost attribute and component size factors of the required (unknown) component, C_b and A_B are the known component-based cost and size factors, and n is the exponent for cost correlation. However, this exponent n changes per equipment type, e.g. 0.94 for generator (see Table 1), which provides a rough approximations of the actual cost. When the technical details of selected components are obtainable, but their specific component cost are unknown, the costs may be computed using the actual component cost correlations. Hence, the actual component cost, C_p can simply be expressed using Eqn. (7) [23]:

$$C_P = C_B \cdot F_M \cdot F_T \qquad (7)$$

Where F_M is the material factor and F_T is the correction factor. Finally, the costs of materials and labour were subject to inflation, implying that the cost figures for a variety of years were directly incomparable. The best manner for updating the historical data is through composite cost indices, which are the weighted average indices of various components costs. The composite cost indices can be computed using the Eqn. (8) [20]:

$$C_x = C_y\left(\frac{I_x}{I_y}\right) \qquad (8)$$

Where Cx and Cy are the costs in years' x and y respectively, and Ix and Iy are the cost indices for the respective years. Table 3 presents the thermodynamic parameters and

Table 3. Thermodynamic parameters and estimated component cost coefficient of the simple and recuperative TLC power generator systems

Cycle Configurations	Net Power Output	Basic Component	Obtained Thermodynamic Values	Component Cost Coefficient (A)
Simple	134.1 kW	Feed Pump	$\dot{W}_p$ = 5.003 (hp)	6.7091
		Heater	$\dot{Q}_{in}$ = 610.4 (kJ/kg)	0.0518
		Expander	$\dot{W}_{ex}$ = 139.1 (kW)	139.1
		Condenser	$\dot{Q}_{out}$ = 476.2 (kJ/kg)	0.04
Recuperative	145.9 kW	Feed Pump	$\dot{W}_p$ = 5.003 (hp)	6.7091
		Recuperator	$\dot{Q}_{recup}$ = 436.1 (kJ/kg)	0.037
		Heater	$\dot{Q}_{in}$ = 610.4 (kJ/kg)	0.0518
		Expander	$\dot{W}_{ex}$ = 150.9 (kW)	150.9
		Condenser	$\dot{Q}_{out}$ = 464.5 (kJ/kg)	0.0212

estimated component cost coefficient of the simple and recuperative TLC power generator systems. These were used for computing the component-based costs of the cycles.

Economic Indicators

The feed pump, heater, expander, condenser, and generator, among other essential and auxiliary pieces of equipment, as well as the installation and construction costs, were used to assess the TLCs' overall investment costs. The cash flow for each cycle was the money obtained from the sale of the electricity produced at an energy price and tariff of 0.0675 $/kWh after deducting the variable costs, which included the costs of operation and maintenance. Based on the predetermined assumptions and recommendations made by Fontalvo et al. [22], an estimation of the start-up, other fixed capital investment component, and operation and maintenance costs was made. The following assumptions were made for the economic evaluation of the cycles. The TLC power generator system has a 20-year period of economic life, a capacity factor of 98%, an average inflation rate of 5% and a linear depreciation of over five years. Hence, the specific investment cost (SIC) of the power generator can be simply computed using Eqn. (9) [24]:

$$SIC = \frac{EEC + O\&MC}{\dot{W}_{net}} \tag{9}$$

Where EEC is the estimated equipment cost, O&MC is the operation and maintenance cost and $\dot{W}_{net}$ is the net power output. The investment ratio, the ratio of net electrical power output to the total equipment costs, was utilised for comparing the investment alternatives. Unlike the levelised cost of energy, the investment ratio does not just appraise the time value of money but also consider the investment alternatives. The investment ratio, γ can simply be computed using Eqn. (10) [25]:

$$\gamma = \frac{\dot{W}_{net}}{\sum_{i=1}^{n} Estimate\,Equipment\ Cost_i} \tag{10}$$

Where n and *i* are the index numbers for the main components of the TLC configuration. A 20-year economic life of the system was assumed, and after the 20 years, no salvage value was considered in this study because the systems are assumed to have no salvage value. A 5% interest rate was employed for the analysis, and other assumptions were the electricity price and tariff of ₦24.97 ($0.0675) per kWh for household consumers with demand levels of >5 kW<50 kW as obtained at the Ibadan Electricity Distribution Company (IBEDC), Nigeria [26]. The present value coefficient that correlates with a future cash flow with present value can be computed using Eqn. (11) [24]:

$$\text{First Cash flow} = \text{Yearly Operation Hours} \times \text{Price of Electricity} \times \text{Total power output} \tag{11}$$

Another economic indicator or tool used to evaluate the cycles economic profitability was the net present value (NPV). NPV, the sum of the present values of incoming and outgoing cash flows; i.e., total cash flows during the economic life cycle of an investment over a period of time, can be computed using Eqn. (12) [27]:

$$NPV = B_{t=0} - C_{t=0} = \sum_{j=0}^{n} \frac{B_{t=j}}{(1+i)^j} - \sum_{j=0}^{n} \frac{C_{i=j}}{(1+i)^j} \tag{12}$$

Where, Bt= j denotes the investment's benefit cash flow for each year and Ct= j is the investment's cost cash flow for each year, including cost of installation at the start of system operation. The profitability index (PI) or cost benefit ratio, referred to as an option to express the investment criteria, is an index of the ratio of the benefit cash flow's present value to the investment cost. The PI can be computed using Eqn. (13) [28]:

$$PI = \frac{B_{t=0}}{C_0} = \frac{\sum_{j=0}^{n} \frac{B_{t=j}}{(1+i)^n}}{C_0} \tag{13}$$

The simple PBP computation, a preliminary judgment of economic feasibility, was used to obtain the PBPs of each TLC power generator system employing the simple PBP computation. The PBP, defined as the amount of time required to recover the cost of an investment or the required number of years that the NPV would attain a zero value, is the ratio of the initial investment to the annual return. It may be estimated using Eqn. (14) [29]:

$$Pay\ back\ time = \frac{Initial\ investment\ (\$)}{Annual\ \mathrm{Re}turn} \tag{14}$$

Where the annual return is the product of the energy produced annually (in kWh/year) and the price of energy transmitted (in $/kWh). In these computations, the operation and maintenance costs were neglected because these costs are negligible in comparison with the capital costs and cash flow [30]. The internal rate of return (IRR), defined as the critical interest rate when the NPV is equal to zero, must always be greater than the operating interest rate for an economically viable investment. The IRR may be computed using Eqn. (15) [24,31]:

$$-C_0 + \sum_{t=0}^{n} = \frac{B_t}{(1+IRR)^t} = 0 \tag{15}$$

Thermodynamic Modelling

The different elements of the cycle's steady-state thermodynamic models, corresponding to their thermodynamic processes, were established and implemented using the Engineering Equation Solver (ESS) on the basis of the working conditions and thermo-physical requirements of the described systems [3,5,8]. The working fluid's potential and kinetic energy variations, heat transfer in the cycles, pressure drop, and heat loss by the systems are negligible, as well as the fact that all thermodynamic processes of TLCs and their constituent parts are modelled and implemented at steady-state conditions, are some of the specific philosophical assumptions and other conditions made. By connecting the separate component models of the cycles, the thermodynamic simulation models of the cycles were implemented and established. The following power outputs were obtained: net power output, expander power, pump power, heat input, heat output, and recuperated heat [3,6,8].

Modelling using Aspen Plus

The process simulators Aspen Plus and Aspen HYSYS, which use the sophisticated software interface Aspen Process Economic Analyzer (APEA), were employed for process simulations using the cubic Peng-Robinson equation of state, adopted for computing the thermo-physical parameters of the working fluids. The process simulator's features, including equipment sizing, an information database, and process conditions, made it possible to estimate project costs quickly and precisely [32]. Through the APEA, a method of economic evaluation was used. When integrating the simulation model into APEA, the unit operations were manually created using specific components and matched to distinct equipment cost models. The simple and recuperative TLC power generator systems were developed using important choice criteria (such as component sizes for each design configuration) and their cost assumptions (such as initial investment cost and operation and maintenance cost) to implement the economic evaluation.

Figures 3 and 4 depict the developed thermo-economic feasibility simulation models of the simple and recuperative TLC power generator systems, indicating the key components and the working fluid flow principle. Figure 3 outlines the model of the simple TLC and its working fluid flow principle within the system components. It showed how the process model was not reinforced with IHE. Figure 4 outlines the model of the recuperative TLC and its working fluid flow principle within the system. It depicted how the process model was reinforced with two IHEs used as the recuperator. These two IHE are the components INT1 and INT2, incorporated to bleed heat from the fluid at the expander flow outlet to preheat the feed pump outlet's subcooled liquid before the heating by the heater.

RESULTS AND DISCUSSION

Figure 5 shows the thermal efficiency and net power output variation of the simple and recuperative trilateral cycles (TLCs) with expander inlet pressure at the cycle high temperature of 473 K. Figure 5(a) showed that the simple TLC's thermal efficiency ranged from 20.13% to 21.97%, with a corresponding net work output of 131.6 to 135.1 kW. Figure 5(b) showed that the thermal efficiency of the recuperative TLC ranged from 23.29% to 23.91%, with a corresponding net work output of 145.9 to 152.2 kW. At each cycle's high temperature, they showed that there were maximum limiting and ideal pressures for the thermal efficiencies and their related net work outputs, respectively. As the cycles' inlet pressure limits increased from 2 to 3 MPa,

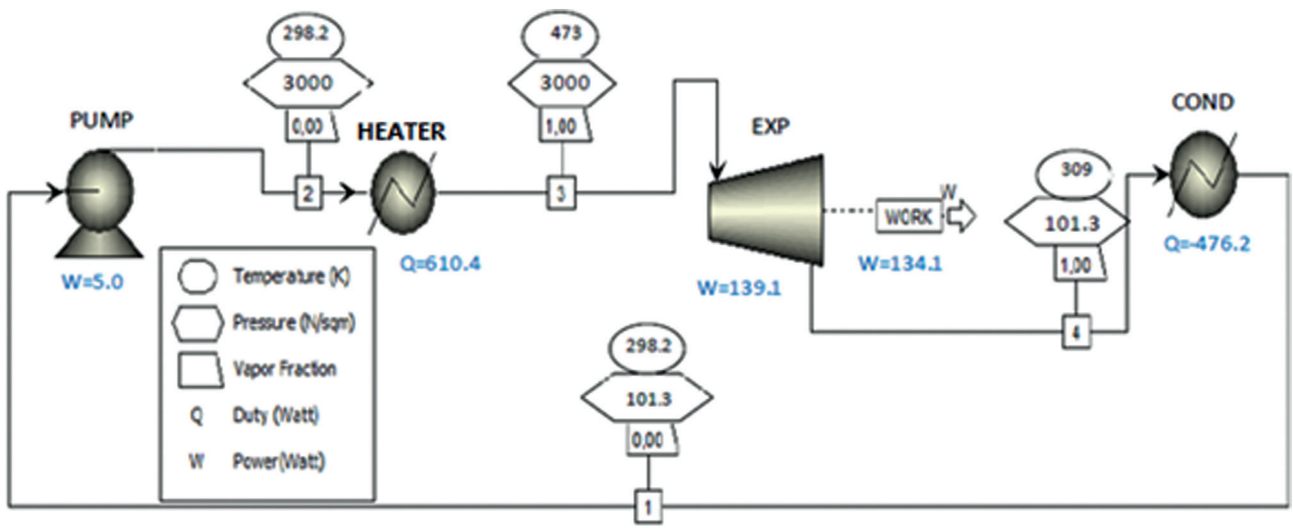


Figure 3. Layout of the simulation model of the simple TLC.

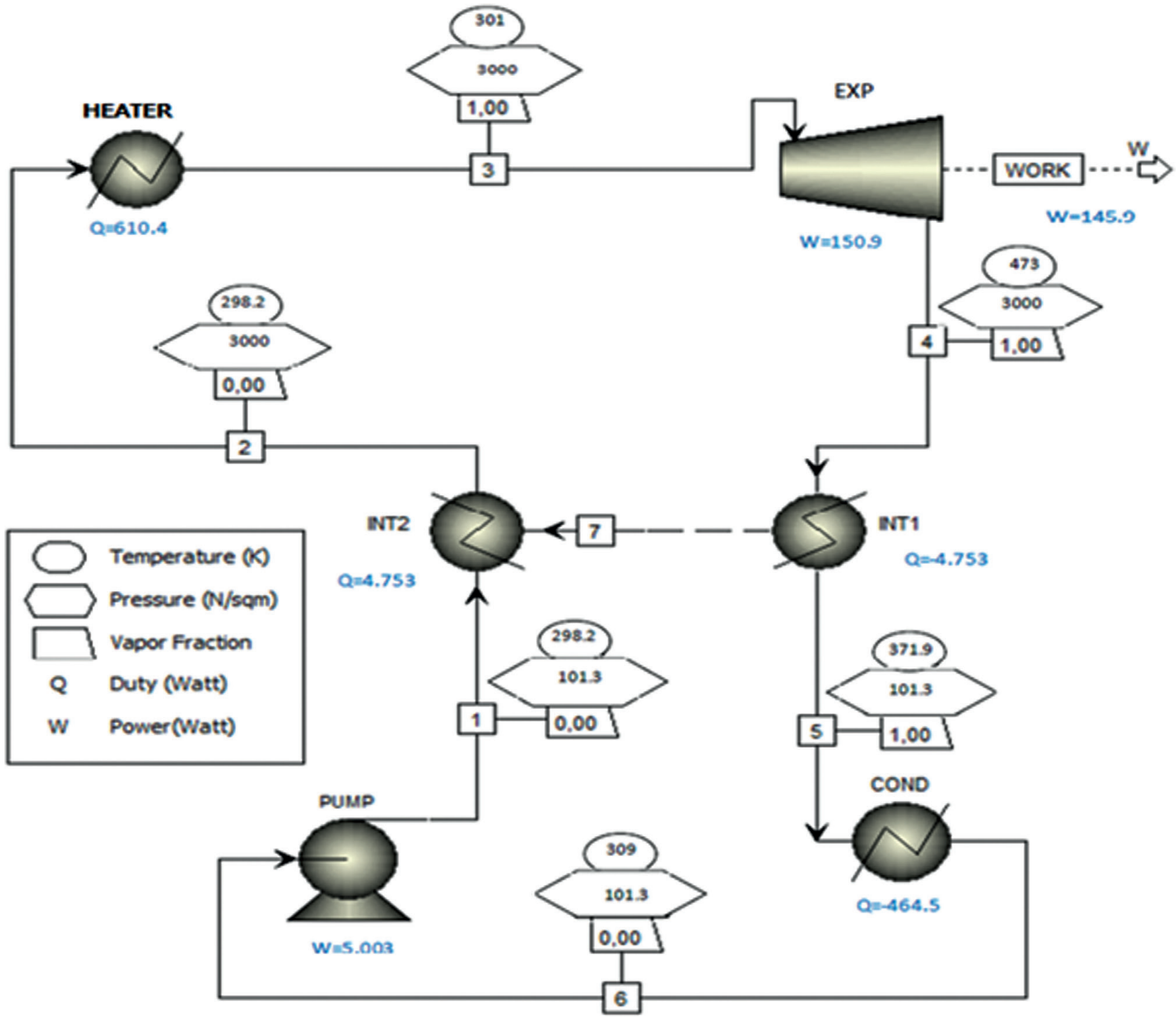
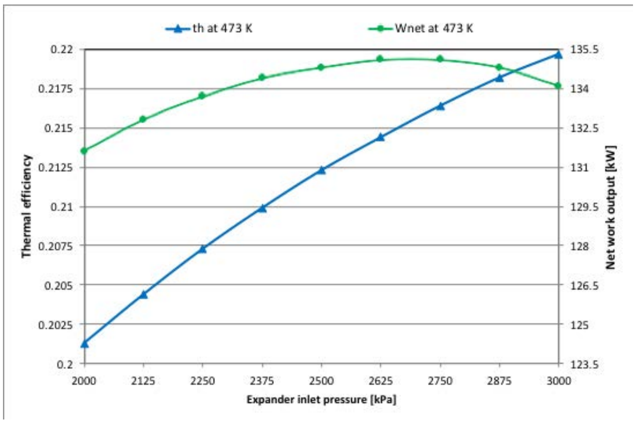


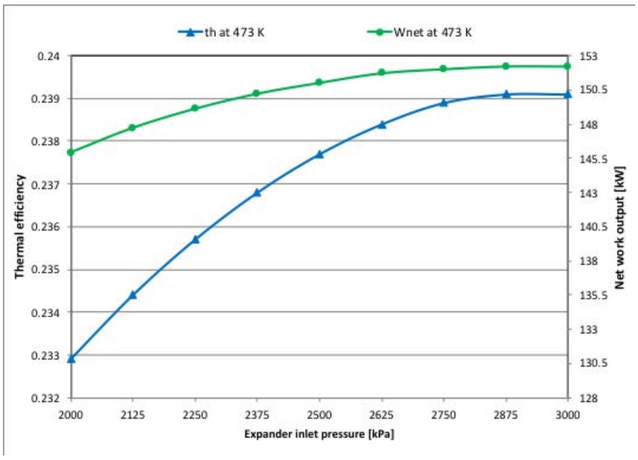
Figure 4. Layout of the simulation model of the recuperative TLC.

their thermal efficiency also increased. Up until the individual optimum pressures were reached, their corresponding net work outputs increased with an increase in inlet pressure and thereafter decreased with an increase in pressure. These increases are due to a rise in the total heat transfer capacity per mass of the working fluid injected into the expander, which rises proportionately with an increase in the expander's intake pressure, indicating an ideal pressure ratio between the expander's inlet and output pressures [8].

Table 4 presents the estimated and percentage costs of the simple and recuperative TLC power generator systems. It depicted that the highest percentage component cost of the simple and recuperative TLCs were the heaters, which had 67.76% and 74.46%, respectively. The cost of the heating for the recuperative TLC was much higher than that of the simple TLC because of the cost variation of the heat exchange area for the recuperation process (i.e., the addition of the internal heat exchanger) and its ancillary equipment. The relative thermodynamic performance improvement of the preheating process augments the high-pressurised subcooled liquid by the feed pump with the bled latent heat from the exhaust of the expander, decreasing the heat load on the condenser. The total heat exchange areas of the heater, recuperator, and condenser are influenced by the operating conditions, which have a direct effect on their costs. It has been established that by minimising the unit heat exchange area with optimal high pressures, the system cost is much lower than maximising the energy performance of the system [33]. The reduction in the quantity of heat input from the heater of the recuperative TLC directly influenced the



a.) Simple TLC



b.) Recuperative TLC

Figure 5. Variation of thermal efficiency and net work output with expander inlet pressure a) simple TLC and b) recuperative TLC.

heat exchange area with a lower value of the component cost coefficient (see Table 4). The high cost of heaters for both systems represents the huge thermal energy added to the cycles [27]. If these component costs can be reduced, the cycles might be viable for electric power generation without massive subsidies.

These findings of the estimated equipment cost for the cycles were computed from the cost of each component of the simple and recuperative TLC power generator systems, respectively. The equipment cost has been reported that it cannot ultimately justify the economic feasibility of any power system due to a lack of inclusion of other investment cost components such as freight, maintenance, engineering, or instrumentation [20,22,33]. Besides, despite the high net power output obtained from the recuperative TLC, more costs were incurred on the equipment to actualise the differential in net power output compared to the simple TLC. However, the equipment cost of the simple TLC power generator system was lower with reasonable net power output, making the simple TLC system more feasible. The total investment costs obtained were $3,303,199.16 and $3,785,549.22 for the simple and recuperative TLC power generator systems, respectively, which compared favourably with the findings of a similar analysis reported by Toffolo *et al.* [23]. This confirmed that a change in the cost of investment causes a relatively greater change in the power system's net present value (NPV).

Based on the simulation experimentation of the process models for the TLC power generator systems with the estimated total cost of investment and thermodynamic parameters (used as the input parameters), the investment ratio (i.e., the ratio of power to cost for the different cycle configurations) and profitability analyses of the systems were

Table 4. Estimated and percentage costs of the simple and recuperative TLC power generator systems

Cycle Configurations	Basic Component	Estimated Component Cost $)	Components Cost (%)
Simple	Feed Pump	71,898.5	14.79
	Heater	279,461.8	57.49
	Expander	89,766.0	18.47
	Condenser	3,605.0	0.74
	Generator	41,410.4	8.51
	Total Estimated Equipment Cost	**486,141.7100**	
Recuperative	Feed Pump	76,668.9	13.76
	Recuperator	66,273.7	11.90
	Heater	279,461.8	50.16
	Expander	89,766.0	16.11
	Condenser	3,549.8	0.64
	Generator	41,410.4	7.43
	Total Estimated Equipment Cost	**557,130.6100**	

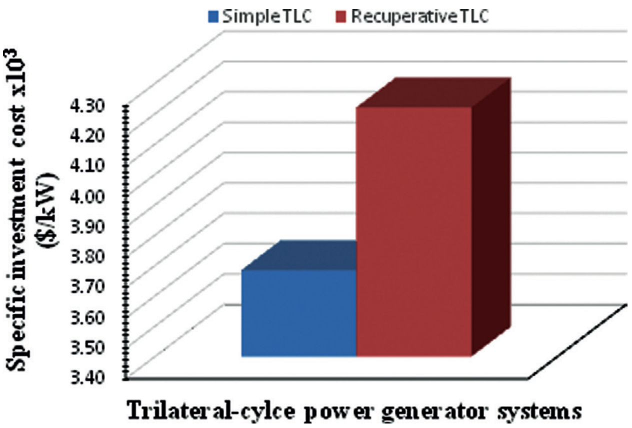


Figure 6. Comparison of the specific investment cost for the trilateral-cycle power generator systems.

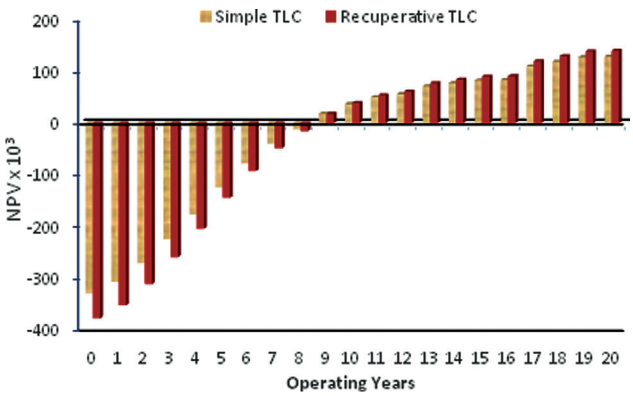


Figure 7. Variation of the estimated NPV with operating year of the trilateral-cycle power generator systems.

carried out. The analyses revealed that the simple TLC was more economical than the recuperative TLC power generator system using *n*-pentane as the working fluid. The simple TLC exhibited a lower investment ratio of 0.24 while the recuperative TLC exhibited a higher investment ratio of 0.28. It has been established that the lower the investment ratio of any power cycle, the more economically feasible and favourable the cycle configuration [25]. The investment ratio was insensitive to the thermodynamic improvement of adding a recuperator to the recuperative TLC. These findings highlight that the choice of any cycle configuration due to the equipment cost could significantly affect the power generation economics. However, power generation may still be quite favourable. The profitability index for simple and recuperative TLC power generator systems was 4.13 and 3.97, respectively. It has been established that for any investment to be efficient, the profitability index is expected to be more than a unit [23]. The internal rate of return (IRR) revealed that the investments on the cycles have a return of 7.34% and 7.14% for the simple and recuperative TLCs, which is higher than the interest rate of 5% and so, a higher yield of the IRR as positive NPVs of the cycles were established. These results suggest that the simple TLC is a more cost-effective cycle when compared with the recuperative TLC at either optimum net power or thermal efficiency.

Figure 6 depicts the comparison of the specific investment cost (SIC) for the simple and recuperative TLC power generator systems. The simple TLC exhibited a lower SIC of 3,683.88 $/kW while the recuperative TLC exhibited a higher SIC of 4,220.41 $/kW. These values compared favourably with the findings of a similar analysis reported by Budisulistyo and Krumdieck [25]. Jung *et al.* [34] carried out a techno-economic feasibility study of an organic Rankine cycle (ORC) for power generation from waste heat of a refinery plant. They reported a SIC of 2,500 to 3,500 $/kW. However, a high value of SIC was obtained for the recuperative TLC due to the price of the additional components such as the recuperator and its ancillaries in the recuperative TLC configuration.

Figure 7 depicts the variation of the estimated NPV with operating years for the simple and recuperative TLC power generator systems. It can be observed that the estimated NPV, i.e., throughout the economic life cycle of the investment cycle, the total cash flows gradually increase with an increase in the number of operating years. The non-uniform gradient can be attributed to variations in electricity prices and tariffs, which are usually subject to review based on the annual inflation rate, fuel costs, generation capacity availability, and subsidies [26]. A comparative assessment of the cumulative NPV curve depicted that the initial cost of investment may be recovered within the economic life cycle of the investment on the cycles; that is, an estimated payback period (PBP) of 8.43 years of operation for the simple TLC compared to 8.55 years for the recuperative TLC. The gradient of the slope of the estimated NPV curves demonstrated that the simple and recuperative TLC power generator systems were both economically feasible. The SIC, electricity price, and tariff have been identified as the major factors that influence the profitability of the investment. It has been established that a reduction in the SIC might be accomplished by enhancing the plant's manufacturing technology and management or by gaining government-offered environmental incentives and subsidies [24,35]. Moreover, the electricity price and tariff rate can possibly increase at a rate greater than inflation because of the various issues that include the volatility of gas prices, foreign exchange rates, and the actual daily generation capacity reflecting the security of supply issues [25].

Figure 8 depicts the variation of the simulated NPV with operating years for the simple and recuperative TLC power generator systems. It can be observed that the

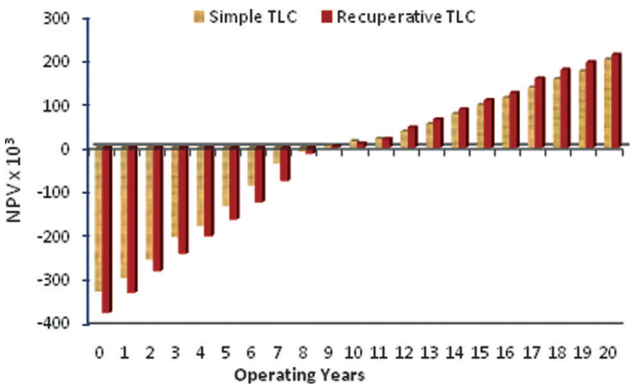


Figure 8. Variation of the simulated NPV with operating years of the trilateral-cycle power generator systems.

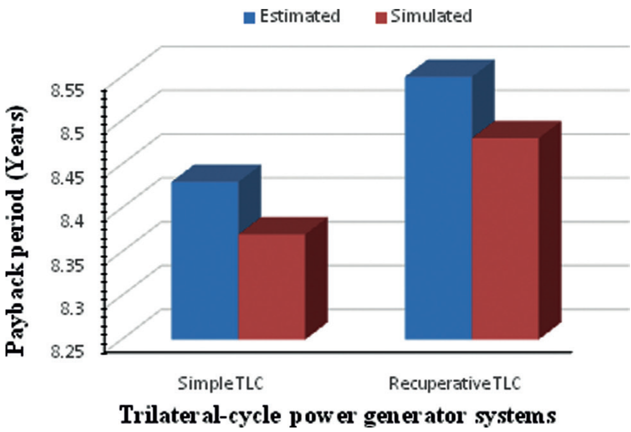


Figure 9. Comparison of the payback periods for the trilateral-cycle power generator systems.

simulated NPV of the investment on the cycles gradually increases with an increase in the number of operating years after investment recovery. A comparative assessment of the cumulative NPV curve depicted that the simulated PBP was 8.37 years of operation for the simple TLC, compared to 8.48 years for recuperative TLC. These simulated values of PBP from the process models of the cycles show an early year of investment recovery for the TLC power generators, which compared favourably with the estimated values of 8.43 years and 8.55 years for the simple and recuperative TLCs, respectively. The gradient of the slope of the simulated NPV curve exhibited that the simple and recuperative TLC power generator systems were both economically feasible. The assessment of NPV against the operating years for the simple and recuperative TLCs exhibited a trend that a longer lifetime of the system would increase the cumulative NPV and as well diminish the discount rate. However, it can be observed that the NPVs of the recuperative TLC increase with the operating years and are much higher than those obtained for simple TLC after the investment cost recovery. This can be attributed to the higher power output that was obtained from the recuperative TLC due to the addition of the recuperator, which directly affects the profit obtained.

Figure 9 depicts the comparison of the PBPs for the simple and recuperative TLC power generator systems. The PBPs demonstrated that investing in the cycles would begin to yield profits around the eighth year of simple TLC operations and the ninth year of recuperative TLC operations for up to 20 years. The closeness in the number of years required for the initial investment cost recovery for the recuperative TLC power generator system can be attributed to its higher power output that consequently increases the annual revenue cost of the system. The simulated values of PBP of the simple TLC exhibited an early year of investment recovery of 8.37 years and the recuperative TLC exhibited an early year of investment recovery of 8.48 years, comparing favourably with their corresponding estimated values of 8.43 years and 8.55 years. Despite the improvement in thermodynamic performance due to the recuperation process, the later investment recovery of the recuperative TLC, compared with the simple TLC power generator, can be attributed to the additional cost of the recuperator, which makes the recuperated system not attractive in most cases [36].

CONCLUSIONS

A thermo-economic analysis of the simple (non-recuperative) and recuperative trilateral cycle (TLC) power generator systems and their cost-benefit analyses were carried out to assess their competitiveness relative to other advanced (modified) Rankine cycles and provide crucial information that cannot be obtained simply from thermodynamic analysis. For this study, the process models of the simple and recuperative TLC were developed, established, and implemented using Aspen Plus to carry out their feasibility study and cost-benefit analysis. The specific investment costs of the simple and recuperative TLCs were 3,683.88 $/kW and 4,220.41 $/kW, and their profitability indexes were 4.30 and 4.08, and their payback periods (PBPs) were 8.43 years and 8.55 years, respectively. The simple TLC exhibited a lower investment ratio of 0.24 compared to a higher investment ratio of 0.28 for the recuperative TLC. These economic values suggest that the simple TLC power generator system is more cost-effective when compared with the recuperative TLC because the thermodynamic performance improvement scheme of the recuperation process (i.e., the addition of an internal heat exchanger) and water cooling savings do not recompense the associated cost, making it unattractive at most operating conditions.

AUTHORSHIP CONTRIBUTIONS

Concept – I.A.; Supervision – H.A.; Visualisation – H.A.A.; Reviewing and Editing – H.A.A.; Modelling and

Simulation– I.A., H.K.I; Writing – H.A.A., I.A., H.K.I.; Draft Preparation and Final Editing: I.A., H.K.I

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary thermodynamic data analysed to support the findings are openly available in [dspace.lib.cranfield.ac.uk/handle] at http://doi.org/dspace.lib.cranfield.ac.uk/handle/1826/9202, reference number [#3].

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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