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Improvement of the Energy System of a Nepali Village Through Innovative Exploitation of Local Resources

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Abstract

Nepal is one of the less industrialized Countries and does not have fossil fuel reserves. In this scenario, a better exploitation of energy resources is a key factor to start improving the country's overall energy system. For these reasons, the aim of this work, which is the result of a collaboration between two research groups from different countries, is the design of an ORC which recovers the discharged heat by an existing ICE: the integrated system will supply electricity to a small Nepali village, contributing to a little rise of the life standard of a small and poor community.

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Keywords: Organic Rankine Cycle; Waste Heat Recovery Unit; Plant Design; Energy Efficiency; Nepal

1. Introduction

Nepal is a mountainous landlocked with an area of 147,181 km^2 and a total population of 27.2 million (2013 estimation). It is one of the poorest underdeveloped countries in the world with an annual per capita income of 500$ [1] but the population continues growing rapidly despite various policies to slow it down [2]. 85% of the population lives in rural areas; therefore Nepal can be considered as an agrarian country.

Nepal does not have fossil fuel reserves but is rich in water and biomass. The hydropower development potential is estimated at about 83 GW but the current exploitation level is about 635 MW due to the high investments costs [3]. In fact, hydropower, solar and wind contribute for only 0.7% of the total energy consumption while 87.1% is

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Nomenclature

COND	Condenser
EXP	Expander
ICE	Internal Combustion Engine
MHX	Main Heat Exchanger
ORC	Organic Rankine Cycle
p	pressure, bar
RC	Recuperative cycle
REC	Recuperator
RES	Renewable Energy Sources
SC	Simple cycle with no recuperator
WHRU	Waste Heat Recovery Unit
cond	condensation
critic	critic

covered by wood, crop residues and animal dung. These sources are burnt in open hearths or in traditional stoves with a really low efficiency. Commercial sources like petroleum products, coal and electricity share the remaining 12.2% [1].

The total installed capacity for electricity generation is 696 MW: 473 MW are hydropower plants connected to local grid, 4.5 MW are small isolated hydropower units, 158 MW are hydropower plants connected to the national grid while 60 MW are oil-based plants [3]. Only 40% of the population has access to electricity due to the high cost of grid connection (0.096 $/kWh) and non-renewable fuels (for example the cost of gasoline is 0.79 $/l).

This dramatic situation got further worse in April 2015 with the earthquake: an event that killed over 8,000 people and injured more than 21,000. Being energy one of the most important inputs for economic development it is clear that Nepal needs "new" and "cheap" energy to recover and improve people's life level.

Technologies based on renewable energy sources (RES) offer suitable opportunity to electrify rural areas because they give the possibility of using the local available resources, such as sunlight, biomass, wind and water [4]. However, decentralized electricity systems based on RES have high cost for poor rural population especially in the absence of any access to credit and economy of scale [4]. For these reasons, the fastest and cheapest way to generate electricity is the use of Diesel Internal Combustion Engines (ICEs). In Nepal, several resorts and industries placed in remote areas cover the electricity demand with ICEs fed by diesel because they are characterized by low specific cost and high efficiency, especially in the power range of hundreds of kW to few MW. In addition, Diesel engines can be easily moved from a place to another and rapidly connected to local mini or micro grids. They are also easy to be converted from Diesel to Biofuels/Biogas or equipped with Waste Heat Recovery Units (WHRUs) in order to improve energy efficiency and reduce raw energy demand.

As remarked in [5], in Italy the use of ICEs fed with biomass (such as vegetal oils, biogas or others) guarantees high economic revenue due to incentives, a fact that makes the ICEs operation a viable solution even if no heat is usefully recovered. However, after the earthquake, in Nepal it is really difficult to find out fossil fuels and no incentives have been established to force the RES development. Therefore, the best short time way to increase the electricity production is the possibility of recovering the waste heat from existing engines.

Several technologies are available to recover the energy exhausted by an ICE: mechanical and electrical turbo-compounding, thermoelectric materials and bottoming Rankine cycles [6,7].

Speaking of this last possibility, Organic Rankine Cycles (ORCs) are generally chosen when the thermal power to be recovered has relatively low temperature: this is the case of ICE's waste heat. For example, in [5] a thermodynamic analysis of an ORC that recovers the exhaust heat of a stationary ICE is presented. Three different working fluids and configurations are considered and a parametric analysis is conducted in order to determine the optimal evaporating pressures for each fluid. Also a second law analysis has been performed to determine the best fluid and cycle configuration. The analysis demonstrates that 12% power increase can be achieved by matching the engine with ORC but only a small fraction of the heat released by the engine through the cooling water can be recovered. Also in [9] and [10] a study of working fluid selection has been presented. In [9], nine different pure organic working fluids are selected according to their physical and chemical properties while in [10] the considered fluids are twenty. In [9], results indicate that R11, R141b, R113 and R123 show the highest thermodynamic performances but R245fa and R245ca are the most environment-friendly working fluids. The analysis carried out in [10] additionally shows that R141b, R123 and R245fa bring the highest thermal efficiency and net power output per unit mass flow rate of hot exhaust. These fluids also have the lowest electricity production cost and ratio between the total heat transfer area and the net power output.

In [11], the work aim is to design an ORC able to exploit the heat delivered to the cooling water. Six configurations using ten non-flammable working fluids have been considered while their performances (efficiency, safety, cost and emissions) have been evaluated. Results show that the Double Regenerative ORC configuration using SES36 gets the maximum net efficiency (7.15%) while the single Regenerative ORC using R236fa and the Reheat Regenerative ORC adopting R134a provide a net efficiency of 6.55%. SES36 increments the ICE electrical efficiency up to 5.3% while R236fa and R134a provide an increase of 4.9%.

A study and analysis of the ICE waste heat energy followed by a theoretical investigation on the feasibility of introducing a WHRU in a two-stage turbocharged engine have been presented respectively in [6] and [12] while the transient operation of an ICE with Rankine WHRU has been analyzed in [13]. For a clear overview of the history of ICE exhaust waste heat recovery focusing on ORCs expander and working fluid selection see [14].

Starting from the above mentioned works, it is clear that the insertion of an ORC boosts the engine performance but, in literature, there is a lack regarding the optimum fluid and plant configuration that has to be employed in a 2 MW diesel fueled internal combustion engine. This specific case study has been selected in the present work which is part of a collaboration framework between an Italian and a Nepali research teams that want to develop and install innovative and sustainable power generation units able to improve the living conditions of the inhabitants of a Nepali rural village.

The case study and the analysis of users' demand are presented in Section 2 while the ICE and WHRU models are described in Section 3. Results are presented in Section 4 while conclusions remarks are given in Section 5.

2. The Nepali village

At the time of writing, the Nepali village consists of a sawmill, a tourist resort and twenty small houses used from the sawmill and resort employees (see Fig. 1). The electricity is generated by an Internal Combustion Engine fed by diesel fuel.

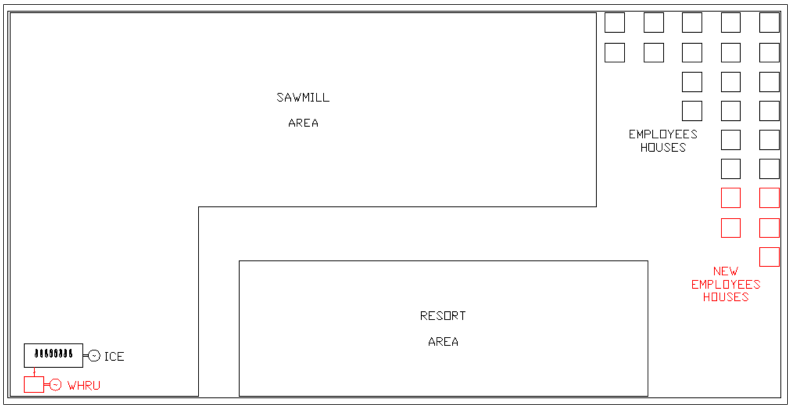

Fig. 1. Layout of the Nepali village (future installations are depicted in red).

In Table 1 the Diesel ICE characteristics are listed, while in Fig. 2 the electricity demand of the sawmill, resort and entire village are reported for a typical working day. The maximum electric power requested during a typical day is 1.9 MW while the heat demand is, at the moment, difficult to estimate for each hour due to the high number of small oil and biomass boilers placed in different locations of the village. There is no local electric grid, then the employees' houses have no access to electricity.

After the earthquake, the request of construction wood has rapidly increased, therefore two additional hacksaws and five houses for the new employees need to be installed. The additional electric power is expected to be 250 kW. Starting from these estimations and considering that the new machines continuously operate during the working hours the existing engine is not able to cover the requested load. In addition, with the goal of improving the employees' living conditions, the houses will be connected to a new micro electric grid. This additional load for the grid will not be a problem for the ICE because the expected power is about 25-30 kW concentrated in non-working hours.

Table 1. Diesel engine specifications.

Parameter	Value
Net electric power at design load	2 MW
Exhaust gases mass flow rate	12490 kg/h
Exhaust gases temperature	440°C
Engine efficiency at design load	41.81%
Engine coolant temperature	85°C

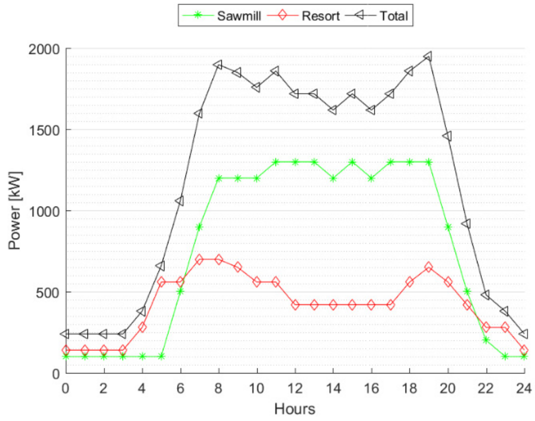

Fig. 2. Resort (red), sawmill (green) and total (black) electric demand.

3. The ICE and ORC model

Being the aim of the present work to provide a viable and innovative solution able to increase the plant electricity production and guarantee the plant reliability and simplicity, the Authors have evaluated the possibility of installing an additional internal combustion engine, a photovoltaic field coupled with a battery stack and a small hydropower plant. But these solutions, unfortunately, are not feasible for economic and technical difficulties: cost of the diesel fuel, prediction of solar irradiance, construction of the hydropower installation.

For these reasons, the possibility of recovering the heat released by the ICE has been evaluated. Being the available heat at medium temperature, an Organic Rankine Cycle WHRU has been considered. Note that the installation of a WHRU guarantees an increment of the plant efficiency but could bring operation and maintenance difficulties in a developing Country.

Nevertheless, with the aim of estimating the ORC production and assessing if the proposed solution is able to provide the requested additional power, the model of the ICE has been developed in MATLAB [15] environment and coupled with the ORC Plant Designer (ORC-PD) tool [16].

The ORC Plant Designer is an in-house simulation tool able to provide the optimal fluid selection and plant configuration of an ORC power unit fed by different heat sources. The optimum working medium is selected among the entire set of fluids available in REFPROP [17] and CoolProp [18] databases. The optimization is performed taking into account a wide range of operating conditions: subcritical and transcritical cycles, regenerative and non-regenerative units and heat transfer made from the hot side and the power cycle (with and without the oil loop). For the selected test case, the heat transfer from the hot side to the power cycle with an intermediate thermal oil loop able to avoid risky contact between the hot fluid and the organic medium has not been considered due to the absence of a high temperature heat source. This configuration is a standard for ORCs coupled with biomass boilers.

In general, a recuperator is installed to preheat the liquid before the Main Heat Exchanger, recovering heat from the outlet flow of the turbine (Fig. 3(b)). The use of a recuperator essentially increases both the cost and the thermal efficiency. In this work, the recuperator efficiency is firstly fixed equal to zero in order to design the simplest and inexpensive unit (Fig. 3(a)). Then, it is considered an optimization variable in order to find the best layout for each working fluid. Being the expander a crucial component, the axial [19] and radial [20] efficiency prediction charts are employed to estimate the expander isentropic efficiency. A cost analysis is also performed to estimate the ORC components costs. In Fig. 3 the simple and recuperative cycle schemes are reported.

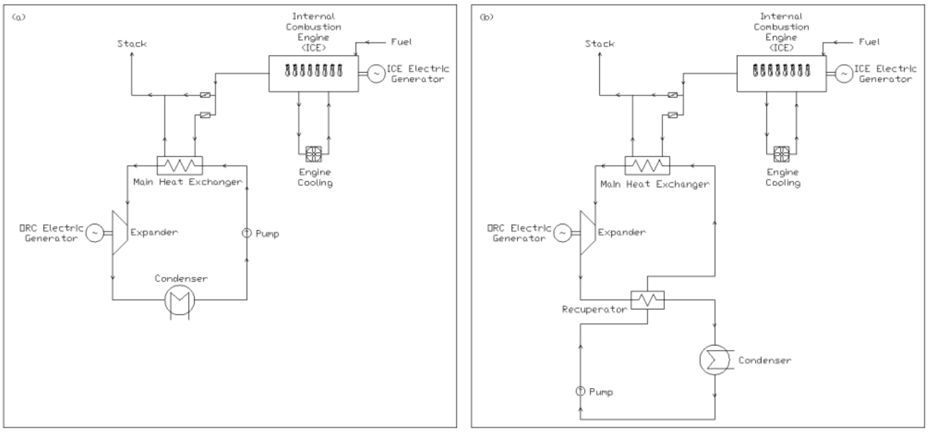

Fig. 3. (a) simple cycle (SC) with no recuperator; (b) recuperative ORC unit (RC).

The possible objective functions that can be selected and optimized, through a simple interface, are seven (see [16]) but in this specific case the maximization of the Net Electric Power has been selected as optimization goal.

The ORC-PD tool inputs are the inlet temperature, pressure and mass flow rate of the engine exhaust gases, the pump mechanical and isentropic efficiency, the electric motor efficiency, the expander mechanical efficiency and the electric generator efficiency while the optimized variables are the exhaust gases outlet temperature, the working fluid evaporation pressure, the turbine inlet temperature, the recuperator efficiency, the condensation pressure and the minimum temperature difference in the condenser, the recuperator and the main heat exchanger. Note that the pinch point position in the heat exchangers is not fixed in order to better match the heat source profile with the working fluid one. In addition, each heat exchanger is discretized in 70 elements and for each element the thermodynamic states of the two streams are computed and the pinch point violation checked.

Several other checks are implemented into the code to avoid not saturated steam at the turbine inlet, low value of steam quality at the turbine outlet and evaporation process into the recuperator (if present). The minimum admissible steam quality at the turbine outlet is set equal to 0.86. Presence of liquid inside the turbine may damage turbine blades and also reduces the isentropic efficiency of the expander. This check is essential due to the presence of wet fluids characterized by negative slope of the saturation vapor curve.

For the optimization the tool uses Genetic Algorithm to find solutions which optimize the objective function; this function is part of the MATLAB optimization toolbox [15].

For further information about the equations implemented into the ORC-PD tool, see [16,21] while machines' and components' efficiency assumed for the ORC optimization and the upper and lower bounds fixed into the ORC plant designer tool are listed in Table 2.

Table 2. Machines' and components' efficiency and upper and lower bounds fixed into the ORC plant designer tool

Parameter	Value
Pump isentropic efficiency	0.78
Electric generator efficiency	0.95
Pump electric motor efficiency	0.89
Pump mechanical efficiency	0.96
Turbine mechanical efficiency	0.93
Exhaust gases outlet temperature	170 ÷ 440°C
Evaporation pressure of the organic medium	$p_{cond} \div p_{critic}$
Recuperator efficiency	0 ÷ 0.8
Minimum temperature difference in the heat exchangers	10 ÷ 40°C
Condensation pressure	40 ÷ 60°C

4. Results and Discussion

At first, the optimization has been carried out with the recuperator efficiency fixed equal to zero (Fig. 3(a)). Then, this parameter has been set as an optimization variable (Fig. 3(b)). Note that the optimum recuperator efficiency for MethylLinoleate (M-linolen) and MethylLinolenate (M-linolea) is equal to zero. Therefore, for these fluids the maximum net electric power is reached with an SC plant layout.

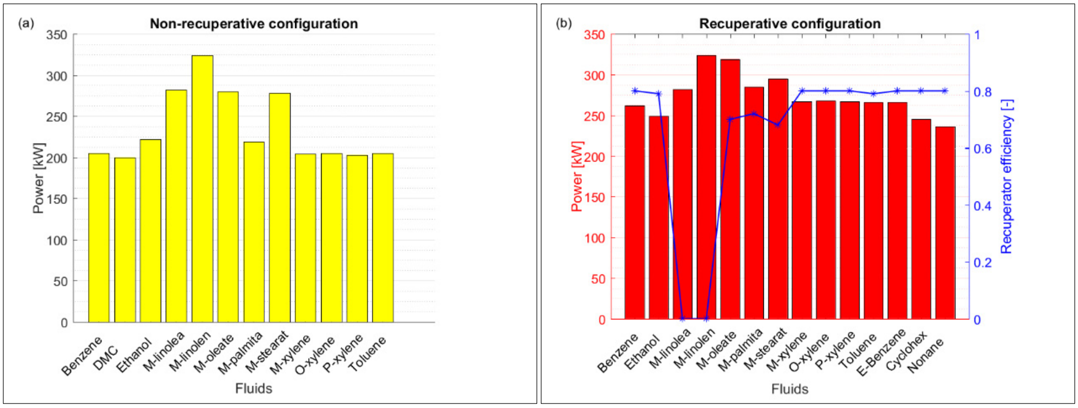

Fig. 3. (a) maximum net electric power for the SC configuration; (b) maximum net electric power for the RC configuration.

As clearly shows in Fig. 3, MethylLinolenate guarantees the highest net electric power (324 kW) with a simple cycle configuration. From a thermodynamic point of view, this medium is a good working fluid candidate because it maximizes the net electric power but is characterized by extremely low condensation pressure: 0.0029 bar at 40°C. These values are not feasible with acceptable costs. In fact, the economic analysis shows a condenser purchasing cost in the case of MethylLinolenate of 4,036,544.9 k$ when for Ethanol is 121 k$. This also brings to a Simple PayBack of about 72 years. Also MethylLinoleate, MethylOleate (M-oleate), MethylPalmitate (M-palmita), MethylStearate (M-stearat) guarantee high net electric power but they require extremely low pressure at the condenser section. Due to technical and economical unfeasibility the above-mentioned media can not be considered as good working fluid candidates.

The highest net electric power is reached with ethanol (222 kW) and O-xylene (268 kW) for the SC and RC configuration, respectively. As clearly depicted in Fig. 3 and 4, a recuperative ORC cycle ensures higher net electric power and equipment costs, 17% and 28% respectively. The higher purchasing costs are due to the presence of the recuperator and the condenser. In particular, at 40°C the O-xylene condensation pressure is 0.02 bar while the ethanol one is 0.18 bar. Being the implemented cost equations able to take into account the pressure effect, low pressure significantly increments the component purchasing cost.

The configuration that guarantees the highest net electric power is the recuperative one (RC), then this configuration has been suggested as the most suitable despite the higher costs related to the presence of the recuperator (see, Fig. 4). Starting from the above-mentioned consideration, the selection of the working fluid has to be done taking into account technical and economical aspects.

M-xylene, P-xylene, E-benzene and Toluene produce a net electric power 1% lower than O-xylene while employing Toluene guarantees a 3.7% reduction of the equipment costs (see Fig. 4(b)). This purchasing costs reduction is mainly related to the condenser costs. In fact, an ORC employing Toluene as working fluid requires a condensation pressure of 0.08 bar (at 40° C) while the M-xylene, P-xylene and E-benzene one is in the range between 0.02 and 0.03 bar. Aspect that increases the plant costs and the Simple PayBack. Therefore, Toluene can be suggested as working fluid. However, the analysis of Fig. 5(a) shows that the cycle is transcritical with an evaporation pressure of 47 bar. A transcritical ORC is not desirable because while it guarantees higher net electric power it also brings control problems and additional costs. For these reasons, the optimization has been run again with an evaporation pressure limit equal to 35 bar. As shown in Fig. 5(b), a RC unit using Toluene with an evaporation pressure lower than 35 bar can also be considered. In this case, the ORC unit produces 262 kW, only 1.5% lower than the transcritical configuration but also 4.3 % lower in term of costs. This difference is related to the cost of the pump: an evaporation pressure of 47 bar increases the costs by 18% while the other devises costs remain more or less the same. This means that also the Simple PayBack time remains the same and equal to 5 years.

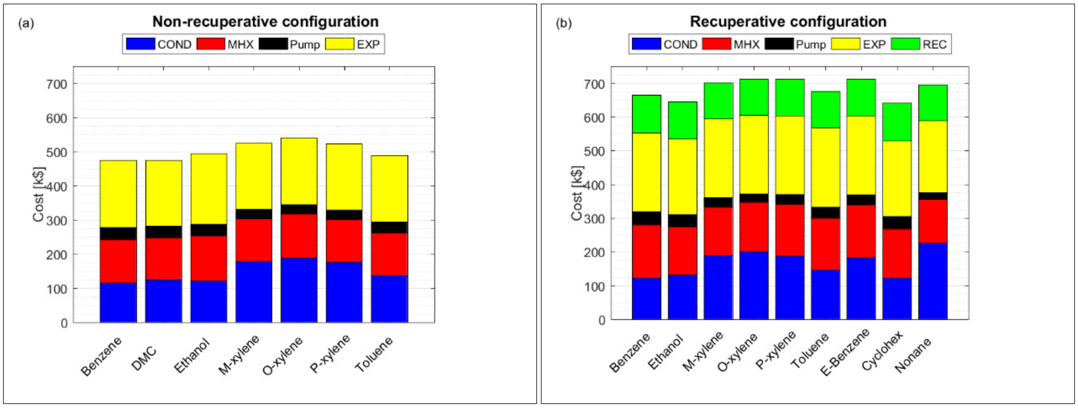

Fig. 4. (a) equipment costs for the SC configuration; (b) equipment costs for the recuperative ORC unit.

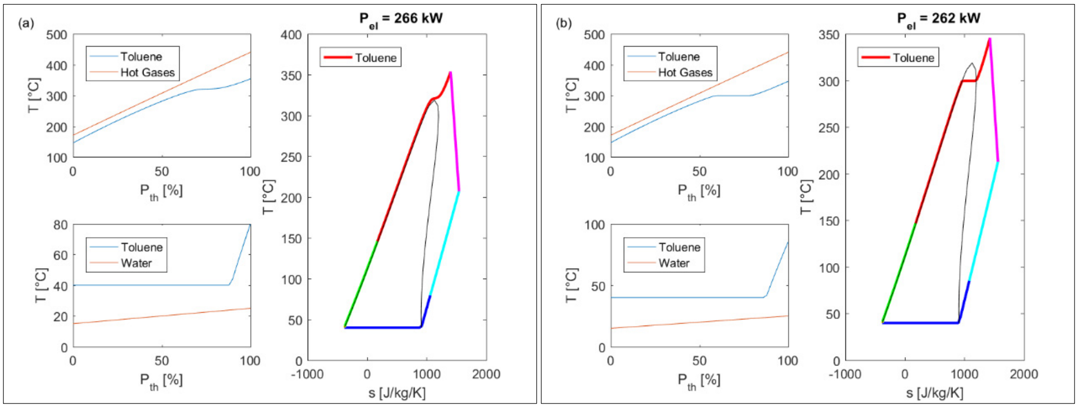

Fig. 5. (a) T-s and T-Q diagrams of the transcritical configuration; (b) T-s and T-Q diagrams of the subcritical configuration.

To sum up, the recuperative subcritical ORC unit employing Toluene as working fluid guarantees 13% higher net electric power and better use of fuel. Adding a WHRU is a good way to increase the plant production but it has high costs (about 2.5 k$/kW). Therefore, in order to reduce the fuel consumption and improve the power generation unit sustainability, the Authors suggest to estimate the village heat demand and biomass potential. After that, the replacement of the diesel oil boiler and engine with a biomass boiler and an ORC recovering energy from the engine and covering the heat and electricity demand can be considered.

5. Conclusions

In some small communities of developing countries, the fastest and cheapest way to generate electricity, without the need of expensive infrastructures, is the employment of Diesel Internal Combustion Engines. In the case of the Nepali village examined in this paper, being fuels difficult to find after the earthquake, the only way to increase the electricity production is to improve the engine efficiency. For this reason, the energy system of the village has been improved with an Organic Rankine Cycle waste heat recovery unit. The ORC unit optimization has been carried out for both simple and recuperative configurations. Results show that the recuperative subcritical ORC unit employing Toluene guarantees 13% higher net electric power and better use of fuel.

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