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Assessment of an organic Rankine cycle and a Kalina cycle for a single source of low-enthalpy geothermal heat

Evaluación de un ciclo Rankine orgánico y un ciclo Kalina para una misma fuente de calor geotérmica de baja entalpía

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Abstract

This article shows the simulation results of an organic Rankine cycle (ORC) operating with the R134a working fluid and a Kalina Cycle operating with the ammonia-water mixture in order to compare the results and detect the better performing cycle. The working conditions were attained through a field visit to the town of Los Negritos, Michoacán, where it was determined that it is a superficial low-enthalpy source. To conduct the simulations, the Software Engineering Equation Solver (EES^{TM}) was employed. In the ORC, a net electric power output of 10.97 kWe was obtained with 4.58% cycle efficiency, while with the Kalina cycle, a net power output of 5.53 kWe was obtained along with an overall efficiency of 6.61%.

Energy evaluation, Geothermal energy, Thermodynamic cycles

Resumen

El siguiente trabajo muestra los resultados de la simulación de un Ciclo Rankiene Orgánico (ORC) operando con el fluido de trabajo R134a y un Ciclo Kalina operando con la mezcla amoniaco-agua, con la finalidad de comparar los resultados y detectar el ciclo con mejor desempeño. Las condiciones de trabajo se obtuvieron a través de una visita de campo a la localidad Los Negritos, Michoacán, donde se determinó que se trata de una fuente de baja entalpía superficial. Para realizar las simulaciones se empleó el Software Engineering Equation Solver (EES^{TM}). En el ORC se obtuvo una potencia eléctrica neta de salida de 10.97kWe con una eficiencia del ciclo de 4.58%, mientras que con el ciclo Kalina se obtuvo una potencia neta de salida de 5.53kWe y una eficiencia global de 6.61%.

Evaluación energética, Energía Geotérmica, Ciclos termodinámicos

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Introduction

Mexico's energy production is primarily based on fossil fuels (86.90%), while renewable resources contribute 11.25%, as seen in Figure 1 (SENER, 2021). However, conducting energy power studies is of vital importance- especially of the energy sources that can be exploited in a reliable and safe way- in order to diversify the national energy matrix and simultaneously focus on distributed, non-centralized generation (Abrigo, 2022). Accordingly, geothermal energy is a viable alternative, given that previously tested technology can be applied (Fridleifsson, 2001; Noorollahi, Shabbir, Siddiqi, Ilyashenko, & Ahmadi, 2019; Palomo-Torrejón, Colmenar-Santos, Rosales-Asensio, & Mur-Pérez, 2021). Renewable energies in Mexico are diversified as seen in Figure 2, where the most exploited or used is biomass (6.34%), firewood (4.87%), followed by geothermal (1.65%), and then cane bagasse (1.47%).

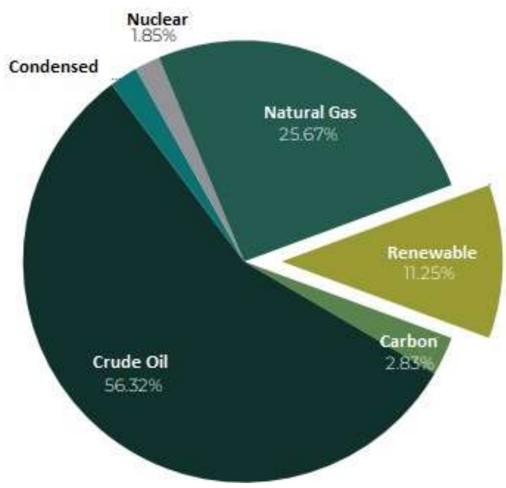

Figure 1 Production of primary energy in Mexico
Source: (SENER, 2021)

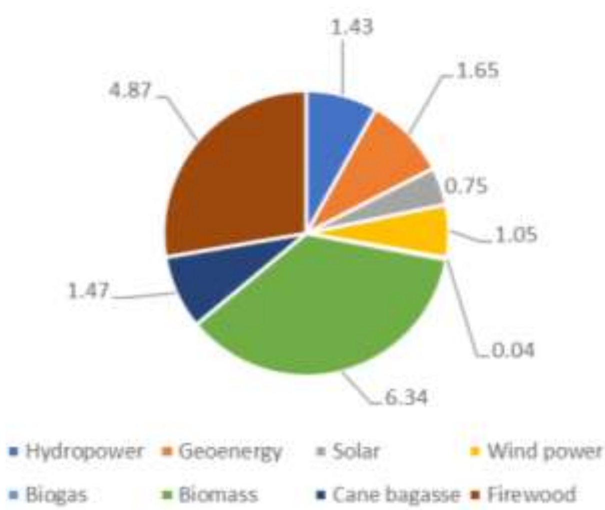

Figure 2 Contribution of renewable energies
Source: *(SIE, 2022)*

By 2020, Mexico was in sixth place worldwide in regard to the use of its geothermal energy resources (Huttrer, 2020). Currently, there are plants established in Cierro Prieto, Los Azufres, Los Humeros, Tres Vírgenes, and Domo San Pedro (Villeda, Zúñiga, & Flores, 2021). The state of Michoacán is located on the Trans-Mexican Volcanic Belt (Gómez-Tuena, Orozco-Esquivel, & Ferrari, 2005), where in addition to there being manifestations of geothermal energy in the Los Azufres zone, sites in the Ciénega de Chapala Region have been studied and identified, including Ixtlán, Pajacuarán, and Los Negritos (Martínez R. J., 2014).

Accordingly, the Los Negritos zone—located in the Villamar municipality in the state of Michoacán—has been selected to conduct a feasibility study on the generation of electric energy, taking advantage of the zone's superficial geothermal resource (Molés, Navarro-Esbrí, Peris, Mota-Babiloni, & Kontomaris, 2015). To this end, this article analyzes an organic Rankine cycle operating with a R134a working fluid (Vera-Romero, Corona-Ruíz, Reyes, Nava, & Murillo, 2018) and also a Kalina cycle, which is still a steam cycle, but it operates with a binary mixture of ammonia and water (Madhawa Hettiarachchi, Golubovic, Worek, & Ikegami, 2007). The results will be compared to detect the benefits of one cycle in contrast with the other, both for each set of equipment and in general by measuring the net power output and the cycle's overall efficiency.

Metodology

To determine the cycles' operating conditions, a field visit was made to the Los Negritos area, located 10 km east of the city of Sahuayo in the northeast corner of the state of Michoacán, in the municipality of Villamar, one kilometer from Alberca Lake (see Figure 3).

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In this zone, there are volcanic rocks with andesitic and basaltic compositions, with vitreous augite andesites, lacustrine sediments, and manifestations (Le Bert et al., 2011) such as springs, mud volcanoes, and thermal and fumarole manifestations (Figures 4–6). Photographs were taken with a FLUKE Ti32 IR FUSION TECHNOLOGY industrial thermographic camera to identify and obtain a temperature profile of the geothermal manifestations, using SmartView™ software for their proper handling. The images show a visible light spectrum, an image on the thermal scale, and a 3D image of the isotherms (Figure 7).

Figure 3 Los Negritos, Villamar, Michoacán
Source: Google Earth Adaptation

Figure 4 Spring, Los Negritos
Source: Author's File

Figure 5 Mud Volcano, Los Negritos
Source: Author's File

The operating conditions and considerations beginning at the time of the field visit are seen in Table 1. For the simulation, general equations (eqn. 1–15) for balance were used according to the first law of thermodynamics (Table 2), which were programmed in the Engineering Equation Solver (ESS™). Both evaluated cycles are considered steam cycles, mainly based on the conventional Rankine cycle but with some variations, depending on the cycle that is studied. For the ORC, the cycle is the same; the only difference from the conventional cycle is the working fluid: while the conventional cycle operates with water, the ORC employs a working fluid qualified as organic for its physicochemical characteristics (Figure 8). The Kalina cycle does have some substantial differences; mainly, it uses a binary mixture of ammonia and water in addition to being more complex in its constitution and analysis (Figure 9).

Figure 6 Geothermal Manifestation, Los Negritos
Source: Author's File

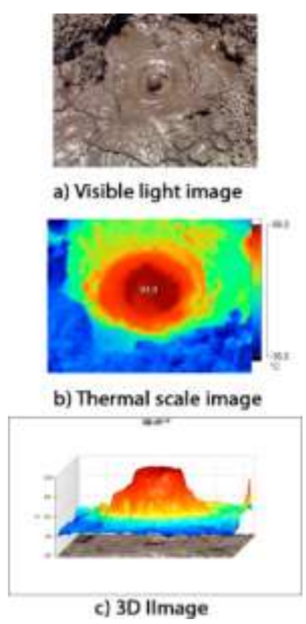

Figure 7 Primary Plain, Los Negritos
Source: Author's File

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Temperature of the geothermal source	92 °C
Temperature difference in the steam generator	10 °C
Temperature difference in the condenser	10 °C
Isentropic efficiency of the steam turbine	85 %
Isentropic efficiency of the pump	80 %
Efficiency of the electric generator	96 %
Effectiveness of the steam generator	100 %
Effectiveness of the heat exchanger inside the greenhouse	70 %
Effectiveness of the regenerator (Kalina)	70 %
Mass flow rate of the geothermal fluid	1 kg/s

Table 1 Conditions and Considerations for the ORC and Kalina Cycle Simulations

Equipment	Equation	No.
Pump (OCR)	$W_P = \dot{m}_{WF}(h_2 - h_1)$	1
	$eff_P = \dfrac{h_{2s} - h_1}{h_2 - h_1}$	2
Pump (Kalina)	$W_P = \dot{m}_{WF}(h_3 - h_2)$	3
	$eff_P = \dfrac{h_{3s} - h_3}{h_3 - h_3}$	4
Evaporator (OCR)	$\dot{Q}_{in} = \dot{m}_{WF}(h_3 - h_2)$	5
Evaporator (Kalina)	$\dot{Q}_{in} = \dot{m}_5(h_5 - h_4)$	6
Turbine (OCR)	$W_T = \dot{m}_{WF}(h_3 - h_4)$	7
	$eff_T = \dfrac{h_3 - h_4}{h_3 - h_{4s}}$	8
Turbine (Kalina)	$W_T = \dot{m}_6(h_6 - h_{10})$	9
Condenser (OCR)	$\dot{Q}_{CON} = \dot{m}_{WF}(h_4 - h_1)$	10
Condenser (Kalina)	$\dot{Q}_{CON} = \dot{m}_1(h_1 - h_2)$	11
Electric Generator (ORC y Kalina)	$\dot{W}_{EG} = (\dot{W}_T - \dot{W}_P) * ef_{EG}$	12
Mass Balance	$\sum \dot{m}_{in} - \sum \dot{m}_{out}$	13
Energy Balance	$\sum \dot{E}_{in} - \sum \dot{E}_{out}$	14
Thermal Efficiency	$eff_{th} = \dfrac{\dot{W}_T - \dot{W}_P}{\dot{Q}_{in}}$	15

Table 2 Equations used for the ORC and Kalina cycle simulations (eqn. 1–15)

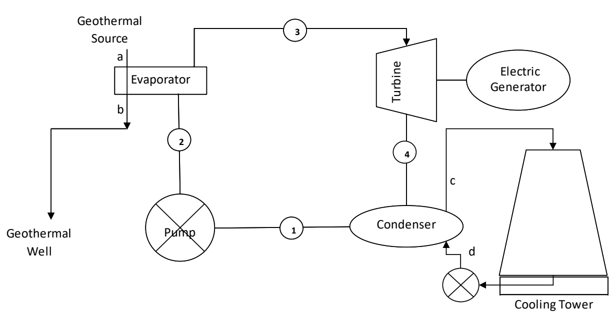

Figure 8 General outline of the organic Rankine cycle

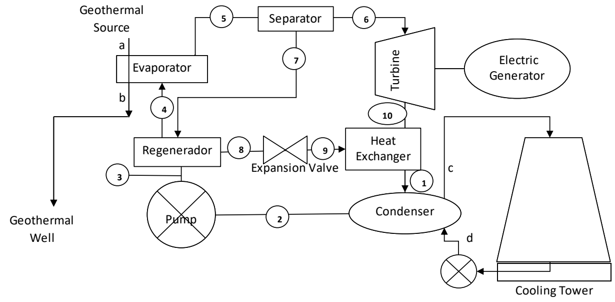

Figure 9 General outline of the Kalina cycle

Results

In the case of the Kalina cycle, before obtaining the results to compare with the ORC, a series of simulations was carried out in which the maximum working pressure and the concentration of ammonia in the mixture varied in order to find the most optimal operating conditions. The results are shown in Table 3. The pressure varied between 10, 20, and 30 bar, while the concentration was between 0.48 and 0.78, with a 0.10 variation for each run. It can be observed that the highest efficiencies were 6.61% at a concentration of 0.48 and a pressure of 10 bar, and an efficiency of 6.80% at a concentration of 0.78 and a pressure of 30 bar. According to these data, the first operating conditions were selected for the work, given that the cost of investment would be lower for having a smaller pump and also needing less replacement working fluid (WF) in the system.

Pressure (bar)	x (Concentration of ammonia in the mixture)	Efficiency of Kalina cycle (%)
10	0.48	6.612
	0.58	4.868
	0.68	2.714
	0.78	1.052
20	0.48	-3.509
	0.58	1.99
	0.68	6.75
	0.78	6.215
30	0.48	-18.7
	0.58	-10.93
	0.68	-5.445
	0.78	6803

Table 3 Comparison of the results of the Kalina cycle simulation in terms of pressure, concentration, and efficiency obtained

The results for each current involved in the ORC are shown in Table 4. Likewise, the results for the Kalina cycle are shown below (Table 5).

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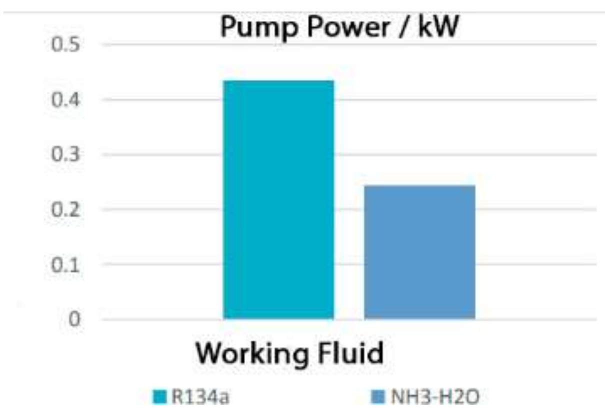
No.	P(MPa)	T(°C)	h(kJ/kg)	s(kJ/kg K)
1	0.7487	29.00	92.13	0.3432
2	1.265	29.38	92.68	0.3435
3	1.265	82.00	312.6	1.025
4	0.7487	64.00	301.6	1.025

Table 4 Simulation results of the ORC

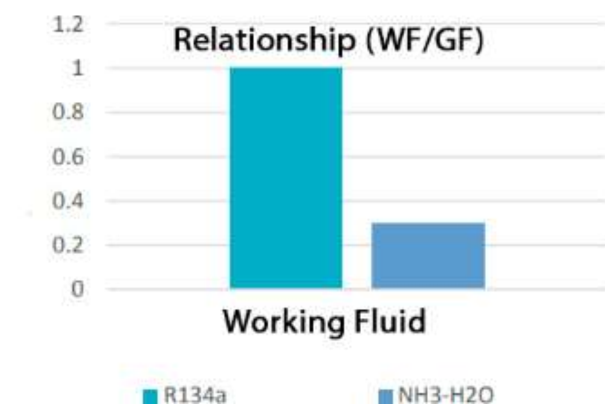
P = 10bar x=0.48							
No	h (kJ/kg)	P (bar)	Quality (Q_v)	s (kJ/kg K)	T (K)	v (m^3/s)	x (kg/kg)
1	152.8	3.175	0.1351	1.127	315.4	0.06462	0.48
2	-109.8	3.175	0	0.2801	302.1	0.00120	0.48
3	-108.8	10	-0.001	0.2808	302.2	0.0012	0.48
4	39.48	10	-0.001	0.7463	335.2	0.00124	0.48
5	321.4	10	0.1381	1.555	355.1	0.02354	0.48
6	1472	10	1	4.893	355.1	0.1628	0.9722
7	137	10	0	1.02	355.1	0.00123	0.4011
8	-35.06	10	-0.001	0.5076	316.6	0.00117	0.4011
9	-35.06	3.175	0.00304	0.5101	315.7	0.0026	0.4011
10	1325	3.175	0.965	4.977	310.7	0.4468	0.9722

Table 5 Simulation results of the Kalina cycle

With the data obtained for both cycles, the next step was to compare the functioning of each set of equipment, where it was observed that the ORC needs more power for the pump (Graphic 1); therefore, it does not only require a higher working power for the cycle, but it also needs a higher mass flow rate of working fluid per unit of geothermal fluid (Graphic 2). For each unit of geothermal fluid, the same amount of working fluid is needed for the ORC, while for the Kalina cycle, only a little less than 0.25 kg of the ammonia-water mixture is needed.



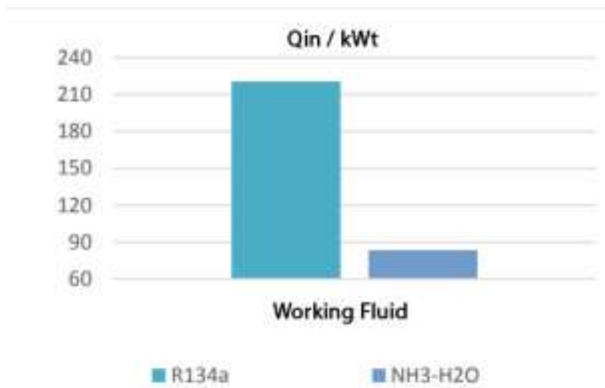
Graphic 1 Power demanded by the pump



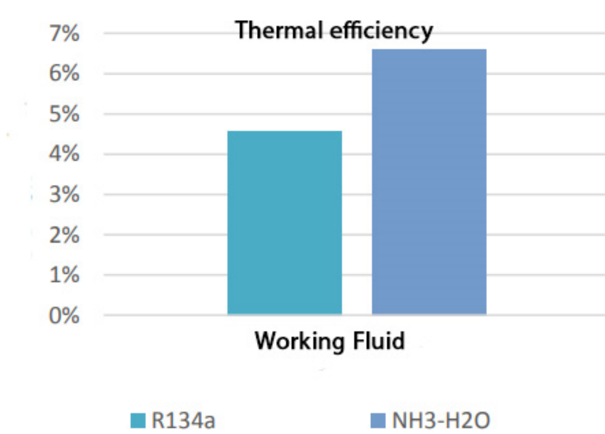
Graphic 2 Mass flow rate of the working fluid in relation to the geothermal fluid

The heat supplied by the geothermal fluid in the part of the steamer can also be considered heat used by the cycle to subsequently be transformed into electrical power. In this area, it can be observed that there is a considerable difference between the heat that one cycle or the other is capable of using; while the heat supplied for the ORC is approximately 220 kWt, the heat used by the Kalina cycle is only 83.58 kWt (Graphic 3). This is most likely because the differences in temperature between the working fluid currents at the steamer's input and output is greater in the ORC compared to in the Kalina. Therefore, the ORC is capable of using the heat better, because when its current 2 reaches the steamer, it has a lower temperature than current 4 of the Kalina cycle; this makes it susceptible to absorbing a higher amount of heat for the cycle.

In the case of the net power output of both cycles and the efficiency obtained respectively, it can be observed that while the Kalina cycle's efficiency (6.61%) was higher than the ORC's efficiency (4.58%), the power output does not behave in the same way (10.54 kWe and 5.77 kWe, respectively), as observed in Graphic 4 and 5.



Graphic 3 Heat supplied in the steamer



Graphic 4 Thermic efficiency obtained for the ORC and Kalina cycle

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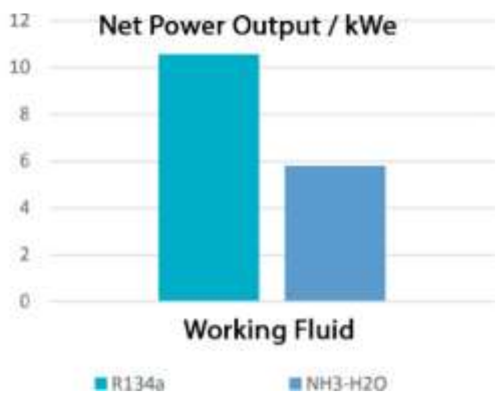
Even though the Kalina cycle was more efficient, it does not produce more power than the ORC. This is because the heat in the steamer that can be used by the ORC is much higher than that used by the Kalina cycle. This is due to the cycles' internal operating conditions and the conditions that this low-enthalpy geothermal source presents, since the geothermal fluid can only transfer heat to the working fluid at a temperature of 82° C.

A more exhaustive analysis could demonstrate more clarity on the latter fact, especially if analyzed according to the second law of thermodynamics, since this would make it possible to observe which of the two cycles destroys more exergy.



Graphic 5 Net power output for both cycles

Conclusions

The analysis indicates that these types of electric power generation plants are possible alternatives for low enthalpy sources, as in the case of the town of Los Negritos, Michoacán. Also, it was detected that while the Kalina cycle has higher thermic efficiency than the ORC cycle, the net power output was greater for the latter. This is attributed to the temperature difference in the steamer; on the cycle side, it is higher for the ORC than for the Kalina. That said, the heat used by the ORC in the steamer is considerably greater than what is used in the Kalina cycle. More exhaustive studies of the analyzed conditions are needed in order to determine the benefits of these cycles.

Referencies

Abrigo, S. A. (2022). *Identificación y aprovechamiento de los recursos energéticos renovables en la provincia del Neuquén, su impacto en la matriz energética de generación eléctrica y socio-económico de escala regional.* (Master). Universidad Nacional del Comahue, Retrieved from http://rdi.uncoma.edu.ar/handle/uncomaid/16716

Fridleifsson, I. B. (2001). Geothermal energy for the benefit of the people. *Renewable and sustainable energy reviews*, *5*(3), 299-312. doi:https://doi.org/10.1016/S1364-0321(01)00002-8

Gómez-Tuena, A., Orozco-Esquivel, M., & Ferrari, L. (2005). Petrogénesis ígnea de la faja volcánica transmexicana. *Boletín de la Sociedad geológica Mexicana*, *57*(3), 227-283. doi:https://doi.org/10.18268/bsgm2005v57n3a2

Huttrer, G. W. (2020). *Geothermal power generation in the world 2015-2020 update report*. Paper presented at the Proceedings world geothermal congress, Reykjavik, Iceland. https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01017.pdf

Le Bert, G. H., Gutiérrez-Negrín, L., Quijano León, H., Ornelas Celis, A., Espíndola, S., & Hernandez Carrillo, I. (2011). *Evaluación de la energía geotérmica en México*. Retrieved from https://www.cre.gob.mx/documento/2026.pdf

Madhawa Hettiarachchi, H., Golubovic, M., Worek, W. M., & Ikegami, Y. (2007). The performance of the Kalina cycle system 11 (KCS-11) with low-temperature heat sources. *J. Energy Resour. Technol.*, *129*(243–247). doi:https://doi.org/10.1115/1.2748815

Martínez R. J., V. R. I., Estrada J. M., Ortiz S. A., Moreno N. I., Montes A.F.G., F. García Á., Mendez R. E. (2014). Geochemical Prospection of the Chapala Ciénega at Michoacán State. *International Journal of Geosciences*, *5*(9), 5. doi:http://dx.doi.org/10.4236/ijg.2014.59086

ISSN-On line: 2444-4987

Molés, F., Navarro-Esbrí, J., Peris, B., Mota-Babiloni, A., & Kontomaris, K. K. (2015). Thermodynamic analysis of a combined organic Rankine cycle and vapor compression cycle system activated with low temperature heat sources using low GWP fluids. *Applied Thermal Engineering, 87*, 444-453. doi:https://doi.org/10.1016/j.applthermaleng.2015.04.083

Noorollahi, Y., Shabbir, M. S., Siddiqi, A. F., Ilyashenko, L. K., & Ahmadi, E. (2019). Review of two decade geothermal energy development in Iran, benefits, challenges, and future policy. *Geothermics*, *77*, 257-266. doi:https://doi.org/10.1016/j.geothermics.2018.10.004

Palomo-Torrejón, E., Colmenar-Santos, A., Rosales-Asensio, E., & Mur-Pérez, F. (2021). Economic and environmental benefits of geothermal energy in industrial processes. *Renewable Energy, 174*, 134-146. doi:https://doi.org/10.1016/j.renene.2021.04.074

SENER. (2021). *BALANCE NACIONAL DE ENERGÍA 2020*. MÉXICO: SECRETARIA DE ENERGÍA Retrieved from https://www.gob.mx/cms/uploads/attachment/file/707654/BALANCE_NACIONAL_ENERGIA_0403.pdf

SIE. (2022). SISTEMA DE INFORMACIÓN ENERGÉTICA Geoenergía. Retrieved from https://sie.energia.gob.mx/bdiController.do?action=temas.

Vera-Romero, I., Corona-Ruíz, S. L., Reyes, J. M., Nava, I. M., & Murillo, O. O. (2018). Comparación térmica de un Ciclo Rankine Orgánico accionado por una fuente geotérmica de calor de baja temperatura. *CONGRESO INTERNACIONAL ANUAL DE LA SOMIM*. Retrieved from http://somim.org.mx/memorias/memorias2018/articulos/A4_120.pdf

Villeda, M. S., Zúñiga, I. Y. C., & Flores, M. D. R. S. (2021). El Desarrollo Energético Sostenible en el Mundo y en México. El caso de la energía geotérmica. *Repositorio de la Red Internacional de Investigadores en Competitividad, 15*(15), 1372-1387. Retrieved from https://www.riico.net/index.php/riico/article/view/2047/1853

ISSN-On line: 2444-4987