AN INTEGRATION OF GEOTHERMAL ENERGY, WASTE, AND COLD ENERGY SYSTEM EMPLOYING THE TECHNOLOGY OF ORGANIC RANKINE CYCLE

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ABSTRACT

Geothermal energy refers to heat sources from the subsurface of the earth that could be directly utilized in many applications like space heating, aquaculture, greenhouses, snow melting, spas, etc., and to generate power by utilizing the dry, binary, flash, and combined thermodynamic cycle. The value chain of geothermal energy utilization is like the oil and gas production, starting from exploration, exploitation and production. Nevertheless, in the case of distribution, it seems that the geothermal energy might not be freely transported (like oil and gas), and geothermal heat must be utilized immediately at a place where it is extracted. This paper presents the concept, calculation model and thermodynamic analysis of a geothermal power system integrated with a thermal energy storage system using dimethyl ether (DME) as a phase-change material and an Organic Rankine Cycle (ORC) system. The DME appears to be an excellent option for this integration because it is a clean substance produced with syngas that could be obtained from several sources (e.g., coal, methanol, biogas, etc.) and distributed in liquefied form, i.e., the liquefied dimethyl ether (LDME). Since it could be extracted from biogas, the system might exploit biogas production technology from waste. The LDME seems to be an excellent way to distribute the DME as liquefication reduces its volume. It is the similar method as it is widely applied for the liquefication of natural gas (LNG), which could be then used to store cold energy. The cold energy has promising potential to generate power by applying a cryogenic power system based on ORC technology. Thanks to the application of LDME and ORC technology, it could be possible, in a certain sense, to transport the geothermal energy at a distance. Therefore, this integrated method tends to be a promising solution for the energy system and the environment. The advantages of this system are to increase the competitiveness of the geothermal system and the improvement of waste management.

1 INTRODUCTION

Geothermal refers to heat coming from the subsurface of the earth, and water (and/or steam) carries this energy to the surface. The value chain of geothermal energy utilization is similar to oil and gas production, starting from exploration, exploitation, and production, but the scheme is different in the case of distribution. It seems that the geothermal heat must be immediately utilized where it is extracted. Several activities might directly utilize this heat for space heating, aquaculture, greenhouses, snow melting, spas, etc. It could also be entirely indirectly exploited that there are several ways to take advantage of the geothermal energy to power, such as dry, flash, binary, and combined thermodynamic cycle (DiPippo, 2015). A steam Rankine Cycle (RC) is a suitable way to transform large-scale geothermal energy into power using the main components of the cycle, i.e., a condenser, a pump, an evaporator, a turbine, and using water as the working fluid in a closed cycle. A consideration of exploiting types of schemes refers to the characteristic of the steam carried geothermal heat, the ability of the turbine, and the economic aspect.

The geothermal water or steam lifted from the subsurface might have different temperatures and contents that it sometimes consists of minerals or other materials. The material contents in the geothermal steam significantly influence the performance of the turbine and might cause erosion on its blades. For this reason, the geothermal steam might not be directly exploited to rotate the turbine, and the schematic of the binary cycle is the promising technology to handle this condition that there is heat transfer to vaporize the working fluid inside the process.

In the case of a steam RC in the binary process, its performance has limitations on recovering the geothermal heat of low thermal potential, therefore, the RC using organic working fluid instead of water as a medium, so-called Organic Rankine Cycle (ORC), is one of the suitable solutions enabling the possibility to exploit the geothermal heat in the various temperature range. Some researchers have examined ORC implemented in the geothermal system. Shengjun *et al.* (2011) reported the investigation on the optimization and performance for subcritical ORC and transcritical power cycle in a low-temperature (i.e., 80-100 °C) binary system. The influence of working fluid on performance and evaluation for geothermal ORC systems was presented by Zhai *et al.* (2014). Also, Zare (2015) investigated three ORC configurations for binary geothermal power plants and proved that the simple ORC has outstanding economic performance.

Since the geothermal heat must be fully extracted at the well found and utilized for power generation, grids might be one of the possible ways for long-distance energy (electricity) transport. This way of transport is possible even for different islands and could be done by subsea grids as seen in Figure 1. Nevertheless, it seems that there might be an economic limitation on building the grid to distribute the electricity from one island to other islands (for example, this applies in the case of building a grid network for many small islands located in geothermally active regions like in Indonesia). Also, many low-temperature geothermal sources tend to be not utilized because it may be not profitable in economic aspect. To tackle these conditions, employing an integrated system might be a promising solution to exploit this geothermal energy. Introducing another cooling source to increase the efficiency of the geothermal cycle could be considered. In the case of energy, dimethyl ether (DME) production is one of the potential schemes that tend to be attractively integrated with geothermal systems. Semelsberger *et al.* (2006) reported that the DME has prominent advantages as a fuel and energy carrier: it could be used for heating and cooking, powering efficient engines, turbines, etc. It could be produced from natural gas, coal, or biomass (e.g., waste biomass) and a wide variant feedstock (Azizi *et al.*, 2014). Among potentially interesting raw sources to produce DME, waste products such as biomass, household, and industrial waste appear to be promising solutions for waste management and the application of an integrated energy system. For that reason, this paper focuses on the concept, calculation model and thermodynamic analysis of a geothermal power system combined with a thermal energy storage system using the DME as a medium. The possibility of power generation utilizing ORC based on the potential waste heat and geothermal is also reported here, and the integrated scheme is also illustrated concerning the geothermal source and the area. The integration system could be also implemented to utilize low-temperature industrial waste heat to develop good efficiency of power generation and sustainability of energy system. Moreover, it appears that the proposed system between geothermal, waste, and cold energy might increase the competitiveness of the geothermal industry that it could use a similar value chain as the oil and gas industry (i.e., using the DME as a cold energy carrier, which could be transported to everywhere).

2 A MODEL OF AN INTEGRATED SYSTEM

For a long-distance, the energy (electricity) could be transferred via the grid, including subsea grids (as is seen in Figure 1). Nevertheless, some limitations (concerning the form and the features of the subsea surface (i.e., topography), seismic activity, distance, installation, maintenance, economical aspect, etc., can be encountered in the place of installation. As an alternative, energy transferred by employing a battery, (in this case, a cold battery which stores energy in liquid form below 0 °C) could be considered in the future. This paper describes the potential design of a power generation system based on integrating a geothermal system with waste and cold energy from DME. Figures 1 and 2 illustrate the combination of the ORC in which DME could also be applied as the working fluid, or the process could use other working fluids.

Figure 2 shows the scheme of the integrated geothermal power generation and value chain of DME as cold energy sources for the cold side of a thermodynamic cycle in the regasification system. In some cases, the cycle might not directly use the geothermal steam because it might contain minerals that lead to corrosion or other damages, so it is necessary to install a pre-treatment to precipitate the calcium ions or others (Finster *et al.*, 2015), as also shown in Figure 2. Four main components of a simple ORC system are an evaporator, an expander coupled with a generator, a condenser, and a working fluid pump. The additional pumps are used to exploit geothermal heat as the heat source for the system and cooling water or cooling air as a heat sink for the system. It seems that the ORC is likely a reasonable technology in this application that, if the proper working fluid is applied, the system could utilize heat sources at a wide range of temperature (i.e., even below 150 °C).

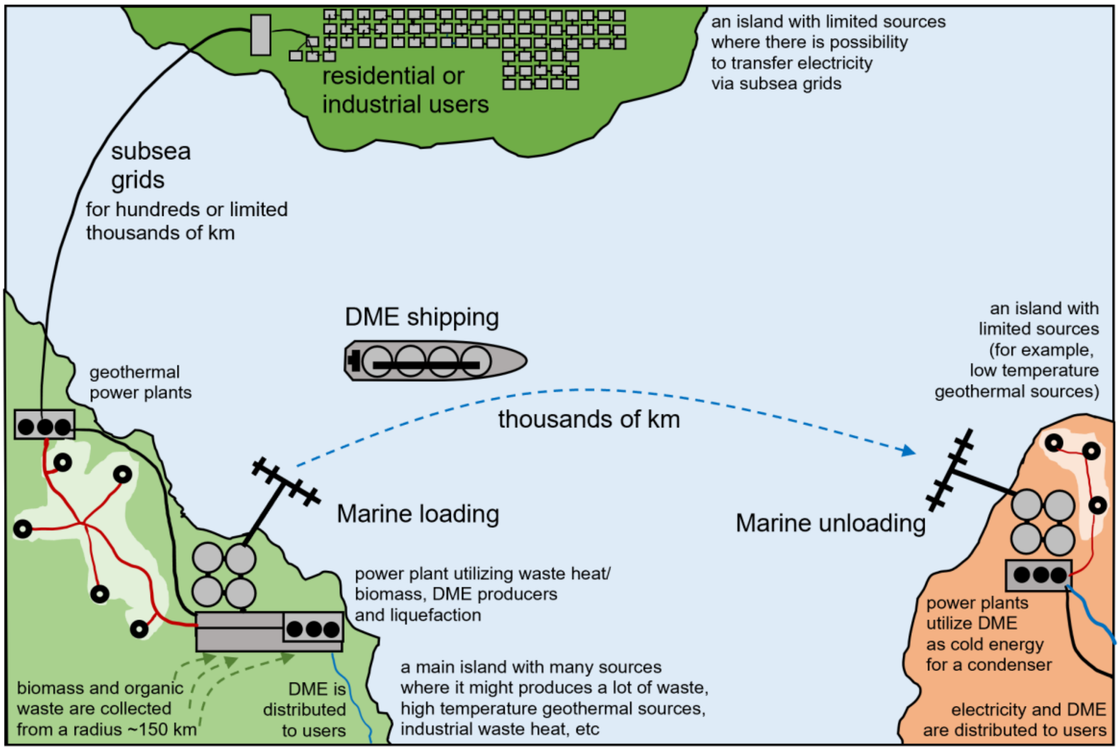

Figure 1: A novelty of integrated system between geothermal, cold energy, and waste.

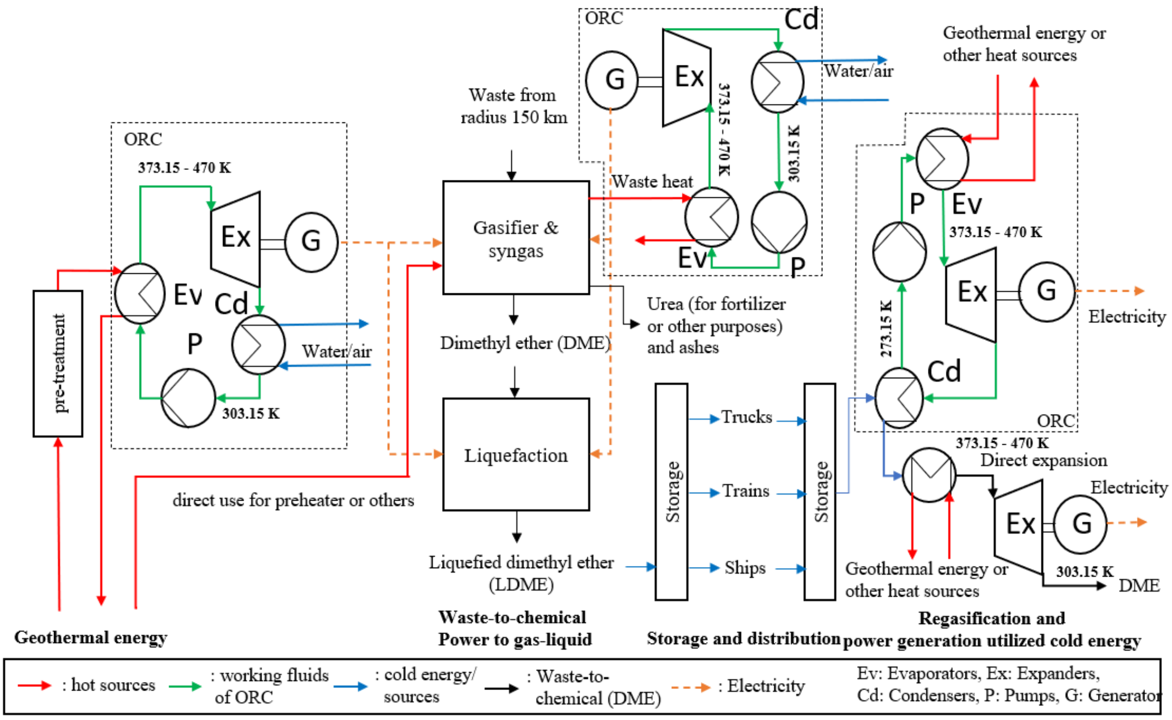

Figure 2: A schematic of an integrated system

Another potential aspect is that a DME producing process could directly utilize geofluid for preheating. Many available sources (e.g., coal, oil, natural gas, biomass, etc.) could be used to produce DME, and there are more likely two processes of synthesizing it directly or indirectly (Bauer and Kruse, 2019). In this case, the process follows the step of gasification, reforming and then syngas is obtained. Besides coal, oil, natural gas, and biomass, exploiting biogas deriving from waste using tri-reforming using unpurified or purified syngas could produce DME (Na *et al.*, 2021). According to the plant layout of wood waste processing to DME from Sadrtdinov *et al.*, (2016), the thermochemical processing consists of pyrolysis and gasification processes where the required gasifier in the proposed system is divided into three stages: stage of heating (60 °C), drying (120 °C), and pyrolysis (650 °C). Then, these steps are followed by the oxidation (1200 °C) and reduction (synthesis gas stage). It also reported that the temperature of produced synthesis gas is around 700 °C. Basu (2013) described that the minimum gasification temperature is in the range 800 – 900 °C for biomass and a minimum of 900 °C for coal. Using waste for DME production is a beneficial aspect that it could be one of the novel and efficient solutions to waste management. The DME production could utilize organic waste, like biomass, an organic household, and organic industrial waste that can be collected nearby the geothermal plant e.g., within a distance of 150 km. Besides DME, the waste also produces other products (e.g. fertilizer); therefore, there is an environmental advantage resulting from its application in DME processing (Silalertruksa and Gheewala, 2013). The way of changing organic waste into DME and other chemical compounds is called the waste-to-chemical process (Antonetti *et al.*, 2017).
The comparison of the characteristic of some commercial gasifiers is reported by Basu (2013). The fixed/moving bed, the fluidized bed, and the entrained bed gasifier types require the temperature range of 450 – 650 °C, 800 – 1000 °C, and over 1260 °C, respectively. Furthermore, Basu (2013) classified the range of applicability for biomass gasifiers from 10 kW up to 1000 MW depending on the types. The operating downdraft starts from 10 kW to 1 MW, updraft from around 1 MW to 10 MW, fluid bed type from 1 MW to 100 MW, and entrained type from around 100 MW to 1000 MW. An example of commercial gasifier performance is given in Table 1.

Table 1: Thermophysical performance of selected commercial gasifiers (Basu, 2013).

Parameters	Bubbling fluidized-bed (BFB) gasifier	Circulating fluidized bed (CFB) gasifier	Fixed bed (updraft) gasifier	Entrained flow gasifier
Feedstock	Biomass	Biomass	Municipal solid waste (MSW)	Coal
Heating value	4 – 13	4 – 7.5	-	9.5
Throughput (ton/day)	4.5 – 181	9 – 108	181	2155
Pressure (bar)	1 – 35	1 – 19	1	30
Temperature (°C)	650 – 950	800 – 1000	-	1400
Gasification medium	O2/air/steam	Air	O2	O2/steam

During the waste-to-chemical process, the waste heat is produced that might be utilized for power generation. The waste heat derives from the excess heat or flue gas, and it looks that ORC is the suitable technology for its recovery and power generation. The mathematical modelling of such a recovery is proposed by Sadrtdinov *et al.*, (2016). The excess heat after wood processing in gasifier and synthesis (from 700 °C to 40-65 °C) and after synthesis of DME (from 300 °C to 40 °C) might be categorized as waste heat that could be replaced into heat absorber to increase the temperature of working fluid in the steam power plant or ORC. Clausen *et al.* (2010) also mentioned that there is a potential source (e.g., the waste heat at the temperature of 600 °C) of a power generation exploiting the waste heat from the DME production.
For a distribution, DME has a similar characteristic as liquefied natural gas (LNG), which can be liquified to shrink its volume. This way liquefied DME (LDME) is obtained. The cooling system is applied to cool down and liquify the DME. The modelling process of the liquefaction is already reported by Sadrtdinov *et al.* (2016), that the temperature of LDME is kept at the temperature of ca. -25 °C. A

study carried out by Salkuyeh *et al.*, (2014) reported that the power consumption of liquefaction DME (the hydration part is included) is 37.3 kJ/kg CO2. The process of changing the phase of DME into liquefied form is similar to the operating method of a storage system, storing the energy via phase change, called power-to-gas (Centi and Perathoner, 2020). Because of its ability, DME could be efficiently and safely transported in a liquefied form. Once transported, the DME might be used for a wide range of applications like an alternative fuel, heating, etc. Since this liquefied form of DME is a typical value chain of cold energy, the transport technology is similar to this used for transporting LNG, including trains, trucks, or ships. The storage is also playing a key role in this scheme that is used to keep the LDME at constant temperature and pressure.

Using DME for other purposes, the regasification system is needed to change the liquid into a gas phase. The heating sources that could be used in the regasification system depending on the area and including air, water, or industrial waste heat. The potential cold energy obtained in this process might be highly exploited for power generation (Daniarta and Imre, 2020). There are two alternatives to exploit the cold energy of LDME for power generation: using it as a cold source for a condenser cooling or heating it at a certain temperature and then directly expand obtained gas. Since the heat source might have relatively low power, the use of heat storage could also be necessary for heat storing and regulating the system. There are many possible applications of heat storage devices for power generation systems (Kolasiński, 2020).

Each component in the ORC system, shown in Figure 2, could be treated as a control volume. The pump forces the working fluid into the evaporator, where it is evaporated until it reaches saturated vapour conditions and then is expanded in the expansion machine (turbine or volumetric expander). The low-pressure vapour is then liquified in the condenser. The following assumptions of the system are made to simplify the thermodynamic analysis of the system. All components are assumed to be in a steady-state. Therefore, the change in the kinetic and potential energy of each component is negligible. The heat losses and pressure drops in the piping connecting the components are negligible.

Moreover, it is assumed that the heat transfer in the pre-heater, the evaporator and the condenser is in the steady-state condition. Furthermore, there are no heat losses, the flow is proceeding at a constant pressure, overall heat transfer coefficients, and specific heats of substances are constant. The state of the working fluid on the condenser outlet is saturated liquid (x=0), and that of the evaporator is saturated vapour (x=1). In this study, the isentropic efficiencies of the expander and the pump are assumed as 0.7. Based on the assumptions described above, the following mass and energy balance equations (see Equations (1) and (2)) are applied to describe the mass and energy flow in the modelled system. The mass and energy balance equation could also be defined for each equipment as it is reported in Table 2.

$$\sum_{\mathrm{in}} \dot{m} = \sum_{\mathrm{out}} \dot{m} \tag{1}$$

$$\dot{Q} - \dot{W} + \sum_{\mathrm{in}} \dot{m}h - \sum_{\mathrm{out}} \dot{m}h = 0 \tag{2}$$

The calculation is computed using MATLAB exploiting thermophysical properties taken from REFPROP (Lemmon *et al.,* 2010) and CoolProp (Bell *et al.,* 2014). Based on the thermophysical properties, the working fluids listed in Table 3 were considered in modelling the ORC system for the geothermal system or other potential heat sources below 200 °C. The mass flow rate of heat sources is assumed at 50 kg/s with a temperature of 25 °C above the temperature of the evaporator, the pinch point is 10 °C. The temperature of the evaporator varies in the operating range up to the critical point, and a condenser is set at 303.15 K (assuming the process utilizes water as cooling sources) and 273.15 K (assuming the process uses DME as cooling sources). In this calculation, only the temperature of the evaporator subjected to the maximal efficiency will be presented because at a certain temperature the overall efficiency of the cycle will drop and it will not be considered as it is seen in the study carried out by Ahmed *et al.,* (2021). The calculation steps of temperature of evaporator is configured at 0.01 K.

Table 2: The mass and energy balance equations of each component and the efficiency for ORC.

Component	Mass balance	Energy balance
Pre-heater	$\dot{m}_{\mathrm{pr}} = \dot{m}_{\mathrm{wf}}$	$\dot{Q}_{\mathrm{pr}} = \dot{m}_{\mathrm{wf}}\,(h_{\mathrm{out,pr}} - h_{\mathrm{in,pr}})$
Evaporator	$\dot{m}_{\mathrm{ev}} = \dot{m}_{\mathrm{wf}}$	$\dot{Q}_{\mathrm{ev}} = \dot{m}_{\mathrm{wf}}\,(h_{\mathrm{out,ev}} - h_{\mathrm{in,ev}})$
Expander	$\dot{m}_{\mathrm{ex}} = \dot{m}_{\mathrm{wf}}$	$\dot{W}_{\mathrm{ex}} = \dot{m}_{\mathrm{wf}}\,(h_{\mathrm{in,ex}} - h_{\mathrm{out,ex}})$ $\dot{W}_{\mathrm{ex}} = \dot{m}_{\mathrm{wf}}\,(h_{\mathrm{in,ex}} - h_{\mathrm{out,is,ex}})\eta_{\mathrm{is,ex}}$
Condenser	$\dot{m}_{\mathrm{cd}} = \dot{m}_{\mathrm{wf}}$	$\dot{Q}_{\mathrm{cd}} = \dot{m}_{\mathrm{wf}}\,(h_{\mathrm{in,cd}} - h_{\mathrm{out,cd}})$
Pump	$\dot{m}_{\mathrm{pm}} = \dot{m}_{\mathrm{wf}}$	$\dot{W}_{\mathrm{pm}} = \dot{m}_{\mathrm{wf}}\,(h_{\mathrm{out,pm}} - h_{\mathrm{in,pm}})$ $\dot{W}_{\mathrm{pm}} = \dot{m}_{\mathrm{wf}}\,(h_{\mathrm{out,is,pm}} - h_{\mathrm{in,pm}}) / \eta_{\mathrm{is,pm}}$
Overall efficiency	$\eta_{\mathrm{ORC}} = \dfrac{\dot{W}_{\mathrm{ex}} - \dot{W}_{\mathrm{pm}}}{\dot{Q}_{\mathrm{pr}} + \dot{Q}_{\mathrm{ev}}}$	

Table 3: The list of working fluids selected for the ORC modelling system retrieved from REFPROP (Lemmon *et al.*, 2010) and CoolProp (Bell *et al.*, 2014)

No	Name of working fluid	CAS no.	Molar Mass (kg/mol)	Boiling point temperature (K)	Triple point temperature (K)
1	Water	7732-18-5	0.018015	373.1243	273.16
2	R152a	75-37-6	0.066051	249.127	154.56
3	R236ea	431-63-0	0.152038	279.322	170
4	R236fa	690-39-1	0.152038	271.66	179.66
5	R245ca	679-86-7	0.1340479	298.412	196
6	RC318	115-25-3	0.20004	267.175	233.35
7	DME	115-10-6	0.04606844	248.368	131.66
8	Isobutane	75-28-5	0.0581222	261.401	113.73
9	Isopentane	78-78-4	0.07214878	300.98	112.65
10	Pentane	109-66-0	0.07214878	309.209	143.47

3 RESULTS AND DISCUSSIONS

The results of a simulation of the ORC system, which scheme is visualized in Figure 2, are presented in the following. Figure 3 shows the variation of the ORC system efficiency vs the temperature of the evaporator for the selected working fluids. An evaporator temperature was varied from 373.15 to 470 K, while a condenser temperature is set fixed to 303.15 K. Within the same operating range, an efficiency of a steam power plant is also provided in Figure 3 as a comparison.

The variation of the cycle efficiency, which is reported in Figure 3, shows that pentane gives good efficiency values compared to other working fluids. Figure 3 also shows that at a specific temperature of the evaporator (ca. 424 K), the cycle using isopentane has similar efficiency to the cycle utilizing

R245ca as working fluid. It could be seen that the difference in the efficiency between isopentane and R245ca is very small, however, isopentane has a more comprehensive operating temperature range which could be treated as its advantage. The similar effect might be seen for R236ea, isobutane, and DME, while the other effect is visible for R236fa and R152a. At the right end of the line plotted for each working fluid in Figure 3, the maximum efficiency of the cycle is obtained. It means that the process at the temperature near the critical point is not considered because it will lead to a drop in cycle efficiency and the expansion process proceeding into highly wet conditions.

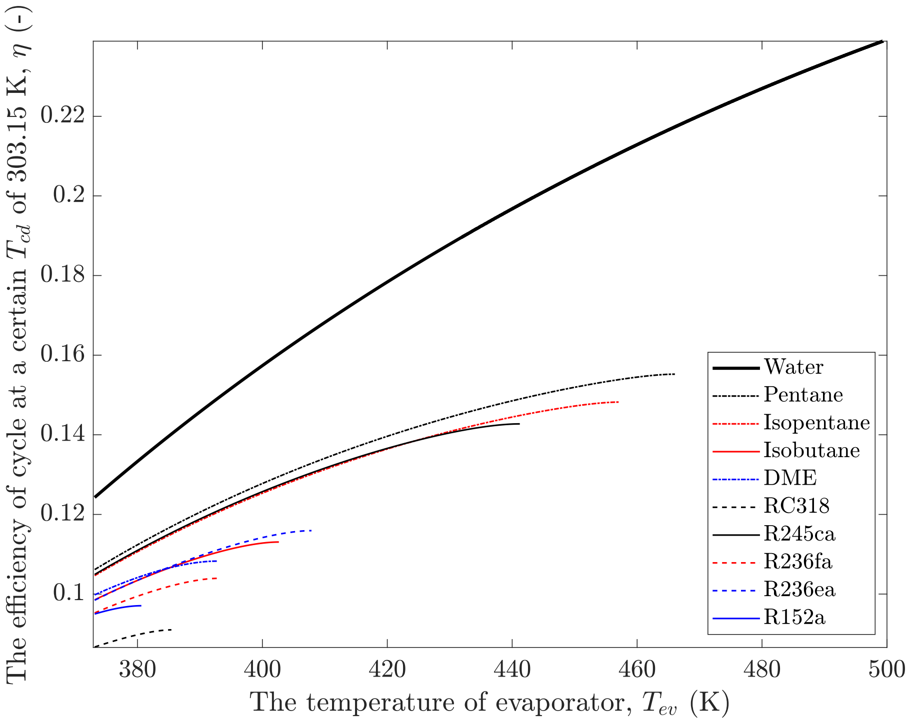

Figure 3: The temperature of the evaporator – the efficiency of the cycle with the temperature of the condenser at 303.15 K for selected working fluids utilized for a geothermal power plant (with the calculation steps of evaporator temperature of 0.01 K).

Figure 3 also illustrates the performance of steam RC (i.e., the cycle using water as a medium). Despite having higher efficiency than the others, it seems that the process needs more significant quantities of heat to evaporate the water inside. The power generated is highly influenced by the mass flow rate of the working fluid inside the cycle as an effect of the mass flow rate of the heat carrier in the heat source. If the heat source characteristic and mass flow rate is fluctuating, partially evaporated or wet steam might be obtained at the outlet of the evaporator) and directed to the expander. This condition will highly influence the performance of the expander and the overall efficiency of the cycle.
Considering the DME as the working fluid in the geothermal cycle cooled by common cooling sources (i.e., air and water) might also refer to the efficiency reported in Figure 3, where the temperature of a condenser is assumed at 303.15 K. Efficiency obtained for DME is relatively low and the maximum temperature of the evaporator is ca. 390 K. Despite having low efficiency, DME is a promising working fluid because it could be liquefied at a temperature below 0 °C. Using it as the working fluid of the cycle combined with cooling sources like air or water might be not recommended. Nevertheless, if DME is utilized as working fluid of cooling sources, it will significantly gain its advantages where the scheme could be seen in Figure 2 (e.g., the process of LDME regasification system combined with ORC and direct expansion process). The efficiency of utilizing cold energy obtained from LDME regasification for power generation by employing ORC could be shown in Figure 4. The efficiency of the ORC using DME as a working fluid and cooling source is boosting its performance because of increasing the operating temperature range of the cycle. Using it as cold energy, it could be assumed that the temperature of the condenser might be lower, at the temperature of about 0 °C (i.e. it could

increase the operating range of the cycle by 30 °C). Nevertheless, it also gives an impact on the maximum efficiency of the process, that decreasing the temperature of the condenser will directly reduce the maximum temperature of the evaporator.

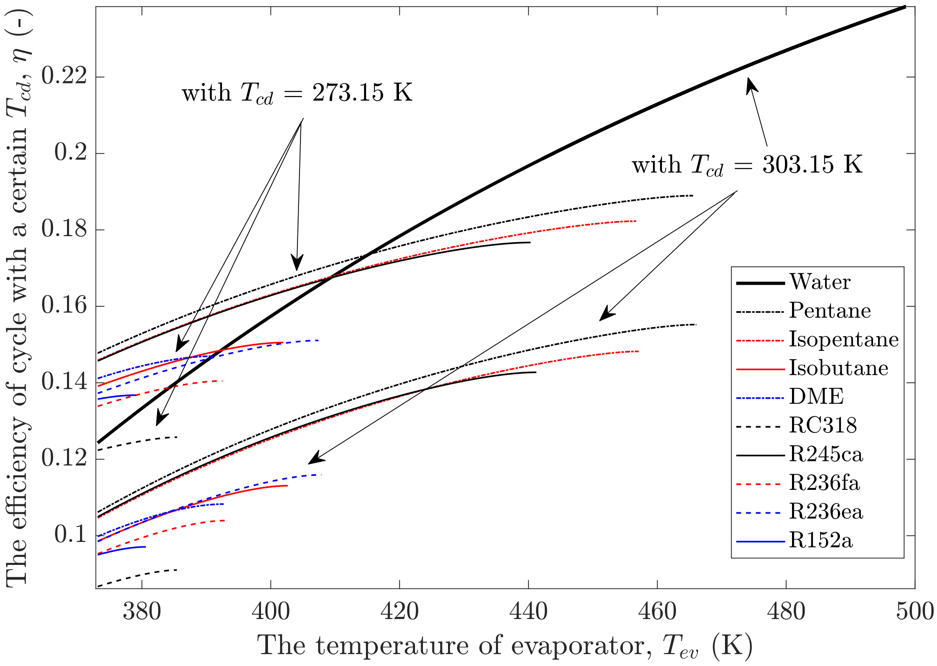

Figure 4: The temperature of evaporator – the efficiency of the cycle with the certain temperature of condenser for selected working fluid utilized for geothermal power plant (with the calculation steps of evaporator temperature of 0.01 K).

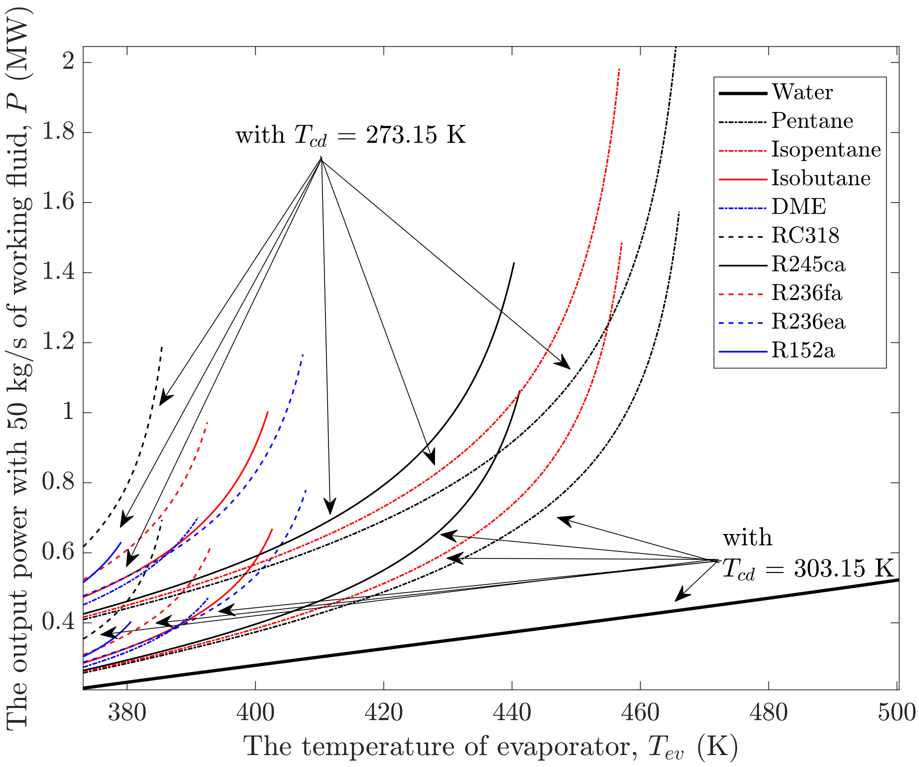

Figure 5: The temperature of evaporator – the output power of the cycle with the certain temperature of condenser for selected working fluid utilized for geothermal power plant (with the calculation steps of evaporator temperature of 0.01 K).

Figure 5 shows the output power generated from the cold utilization of the DME compared to water as cooling sources. It shows that using the same parameter in heat sources (i.e., same temperature range of heat sources and mass flow rate), a conventional RC (using water) produces less output power as it requires more heat to evaporate the water into steams. Moreover, the output power increases while the cycle utilizes the DME as a cooling fluid. Exploiting the DME as a cold energy source in the integrated system is increasing the operating temperature range and the efficiency of the cycle. Additionally, after absorbing heat from the ORC system, it still has the potential to be reheated and then directly expanded in the gas expander for power generation. DME might not be implemented for a steam power plant cooling due to the limitation of the lower temperature related to water freezing. Figure 4 shows that the performance of ORC using R152a, R236ea, R236fa, R245ca, isobutane, isopentane, pentane is also improved. Concerning the advantages of the DME, the proposed integrated system might be a potential solution that could be implemented to generate electricity and be a solution for waste management. As one of the key design issues related to this system, the stability of the mass flow rate of the heat source must be considered in the further studies.

4 CONCLUSIONS

In this paper, the conceptual design of an integrated geothermal, waste, and a cold energy system is presented together with many possibilities of employing an ORC for power generation. The performance evaluation of a cycle is based on the efficiency and the temperature range, while the mass flow rate of the heat source and its stability must be considered in the design stage to determine the power output of the cycle. The selected organic working fluids have been considered in the modelled ORC system; furthermore, it is recommended to implement the modelled DME as a working fluid and cold source in ORC as it seems that it has good efficiency and output power, as described in Figures 4 and 5. This integrated system model, as an alternative to store and distribute the energy for a very long distance, is a promising solution that is boosting the competitiveness of the geothermal system. The production, transportation, and storing system of the DME are the primary concern because it will highly influence power generation downstream where it is utilizing the DME as the primary cooling source of a condenser. Further research on this topic could include the possible application of thermal storage (TES) components in this integrated system.

NOMENCLATURE

Notation

η	efficiency	(-)
h	specific enthalpy	(J/kg)
$\dot{m}$	mass flow rate	(kg/s)
$\dot{Q}$	heat transfer rate	(W)
T	temperature	(K)
$\dot{W}$	power	(W)

Subscript

cd	condenser
ev	evaporator
ex	expander
in	input
is	isentropic
out	output
pm	pump
pr	pre-heater
wf	working fluid

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