



Experimental investigation into the potential of using a shallow ground-cooled condenser in Lebanon

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ABSTRACT

The aim of this paper is to investigate the potential of using shallow geothermal energy in Lebanon for cooling a power cycle. The study includes ground temperature measurement, operating system management, and pressure drop assessment. Temperatures were monitored at six positions underground reaching to a depth of 2 m in Bekaa-Lebanon during the whole of 2020. The temperature sensors were placed at depths of 0.3, 0.6, 1, 1.3, 1.6, and 2 m underground. At 2 m depth, the ground temperature showed high stability with an annual temperature difference of 7 °C, while that of high and low ambient temperatures were 40 °C and 33 °C, respectively. Based on the comparison between ambient and ground temperatures, the ground cooling system can operate 207 days/year partially with full operations of 51 days. This shows that shallow geothermal energy has a great potential to activate a ground-based cooling system in this region. However, to avoid heat accumulation, use of another heat exchanger is recommended to support the ground cooling system. This heat exchanger can also provide coolant compensation when the power cycle is turned off. The pressure drop inside the heat exchangers was found to be highly significant, hence, it was essential to add an intermediate water loop between the power cycle and the ground loop.

1. Introduction

Renewable energy sources (RES) are considered to be the leading contenders for developments of energy systems that reduce or eliminate the use of fossil fuels and thereby decreasing their environmental impacts [1]. However, RES are usually characterized by their stochastic and intermittent natures such as solar [2] and wind [3] energies. This imposes a need to incorporate energy storage systems in order to mitigate fluctuations and provide continuous supply [4,5]. Such systems may also have some impacts on the environment and so making RES-based systems not perfectly green. For these reasons, geothermal energy (GE) can be considered as one of the most attractive energy sources [6,7]. Compared to RES, it is remarkably stable since it is not affected by immediate ambient air changes. GE also encourages the adoption of ideal green systems because the ground can be used as a thermal energy storage medium for other RES such as storing the excess of solar energy

in boreholes [8,9]. One of the most frequent hybridizations is the solar assisted ground source heat pump [10,11]. Such hybrid systems are highly recommended to avoid large ground loop installations and thermal imbalance [12].

GE is mainly classified into two types: deep [13,14] and shallow [15,16]. There is a huge difference between these types since the former utilizes hot geothermal fluid while the latter is based on exchanging heat with the ground via shallow loops. Deep GE can be used to provide heating or activate a power cycle for electricity generation. Geothermal power plants (GPPs) can be found in three forms: dry steam [17,18], flash [19,20], and binary [21,22] cycles. Dry steam GPP is the oldest type such that the geothermal fluid is available in the form of steam only which can be harnessed to drive a turbine-generator. The flash cycle could be used when the geothermal fluid is a mixture of steam and water. The fluid will pass through a flash separator before entering the turbine. The latest version of GPPs is the binary cycle which allows the geothermal fluid to pass through a heat exchanger to heat up another

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Nomenclature

$\dot{m}$	mass flow rate (kg/s)
ΔP	pressure drop (kPa)
D	diameter (m)
f	friction coefficient
h	enthalpy (kJ/kg)
L	length (m)
$\dot{E}$	efficiency
Q	volumetric flow rate (m ³ /s)
Re	Reynold's number
T	temperature (°C)
t	time (hr)
v	velocity (m/s)
W	power (kW)
ρ	density (kg/m ³)

Abbreviations

DCV	directional control valve
DGC	direct ground cooling
EES	Engineering Equation Solver
GCS	ground cooling system
GE	geothermal energy
GHE	ground heat exchanger
GPP	geothermal power plant
I-DGC	indirect ground cooling
ORC	organic Rankine cycle
RES	renewable energy sources

Subscripts

f	working fluid
g	ground
p	pump
t	turbine

working fluid. GPPs have been also developed to cope with advanced types of applications such as hydrogen production [23,24]. In shallow GE systems, ground loops are used to provide heating or cooling. Open ground loops are installed when there is enough amount of shallow water [25,26]. However, ground heat exchangers (GHEs) are used more frequently since they are based on extracting/releasing heat from/to the ground [27,28]. GHEs can be mainly installed vertically [29,30] or horizontally [31,32] depending on the available shallow geothermal conditions. There are two types of shallow GE systems: earth air heat exchanger [33,34] and ground source heat pump [35,36].

One of the latest developments of GE systems is the use of a ground-cooled condenser as shown in Fig. 1 [37,38]. This has shown a great

potential to use shallow geothermal energy for cooling power cycles and especially in case of low-grade energy sources. Thus, it has an indirect benefit on decreasing the environmental impacts of fossil fuels since it allows the extraction of extra amount of power by introducing it as a waste heat recovery system [39,40]. Even though, heat recovery could be used without the installation of a ground-cooled condenser, the generated power would be very limited due to the high ambient temperatures during the most hours of daytime. Therefore, the ground-cooled condenser takes advantage of the low ground temperature during the day allowing more effective working fluid expansion in the turbine. It was reported in Ref. [38] that the ground-cooled condenser can enhance the net output power of the cycle by 7.35%, 12.13% and

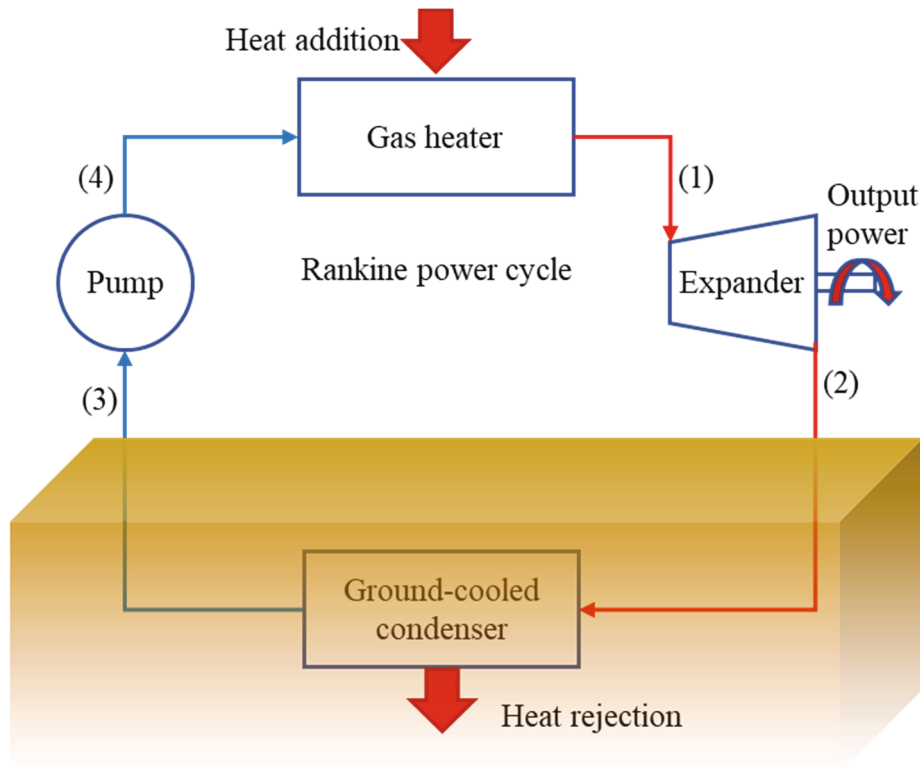


Figure 1: Rankine cycle combined with a ground-cooled condenser

Fig. 1. Rankine cycle combined with a ground-cooled condenser.

8.77% for R123, R124 and R245fa, respectively at an expander inlet pressure of 3 MPa.

This research aims to study the potential of shallow geothermal energy in Lebanon. The ground temperature was monitored in Bekaa-Lebanon (2020) and compared with the highest and lowest ambient air temperatures. The sensors of temperatures were placed at depths of 0.3 m, 0.6 m, 1 m, 1.3 m, 1.6 m, and 2 m underground. Based on the results of the experimental study, the system has been optimized, and the operating modes of the ground cooling system are then presented considering the effect of pressure drop in the heat exchangers.

2. Experimental setup

The setup used to measure the ground temperature is presented in Fig. 2 including digital meter and thermocouples. The digital meter used has an accuracy of 0.5% of full-scale deflection as stated by the manufacturer and can measure a range of temperature between -9°C and 99°C , making it suitable for this experiment. It was a new device hence the calibration was provided by the manufacturer. Six thermocouples of type HT15T are inserted under the ground as shown in Fig. 2. The measuring device has a fast response speed of 4.5 s with a low power consumption (less than 3 VA). It could be easily used as depicted in Fig. 2. The thermocouples used have an error margin of ± 1 . It was also mentioned in the operation instructions of the digital panel meter that the best applicable temperature range is $0\text{--}50^{\circ}\text{C}$. This also makes the device more accurate in this experiment since the ground temperature in Bekaa-Lebanon is always within this range as will be presented in the next section. However, this accuracy is only valid for temperature measurements when the humidity is below 85%. Thus, it is decided to undertake the experiment in a place where the soil is dry all over the year, so not to compromise the accuracy of the results, especially for shallower ground temperatures. For this reason, the results obtained at a maximum depth of 2 m correspond to the most reliable collected data. To check further the reliability of the obtained results, the temperature variation was monitored precisely and especially during the winter season when raining. Accordingly, there was no significant variations in the corresponding values.

3. Ground temperature measurement

Fig. 3 shows the recorded ambient air and ground temperatures during 2020 in Bekaa-Lebanon. It can be seen that the ambient

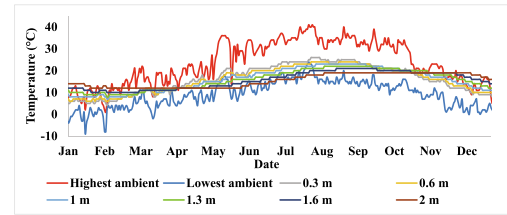


Fig. 3. Ambient and ground temperature measurement in Bekaa-Lebanon during 2020.

temperatures fluctuate significantly while the ground temperatures are considerably stable. As the depth increases the stability increases in which the curve corresponding to the depth of 2 m represents the least temperature fluctuations. During 2020, the maximum temperature difference at 2 m was 7°C since the temperature varied between 12°C and 19°C . This shows the great potential of using ground-cooled condenser in this location and mainly because the ground temperature is nearer to the lowest ambient temperature. Due to the stability recorded at 2 m, this depth will be considered as a reference for the ground temperature in the upcoming analyses.

The ground temperatures in Bekaa are almost constant compared to the ambient air temperature due to the high fluctuations and temperature differences between ambient highest and lowest values during the day. This makes the use of shallow GE very important to reduce fluctuations in energy related systems because even at very shallow depths, the ground temperature is more stable than that of ambient air as shown in Fig. 4. The results show that the annual average values of all ground temperatures are approximately equal to 15.5°C . This makes the results reliable revealing the effect of ground layers on each other which can be noticed from the different temperature variations all over the year but almost equal average temperatures.

The highest, lowest, and average daily ambient air temperatures highly fluctuate compared to that of the ground at 2 m depth as shown in Fig. 5, while the annual ground and ambient average temperatures are almost the same ($15.5\text{--}16^{\circ}\text{C}$). However, it is essential to mention that this comparison is missing a crucial part which is that peak loads are usually reported during the daytime when the ambient temperature is relatively high. This makes the use of ground-cooled condenser very efficient for two main reasons that are stability and low temperature compared to that of ambient during operating hours. It is also expected

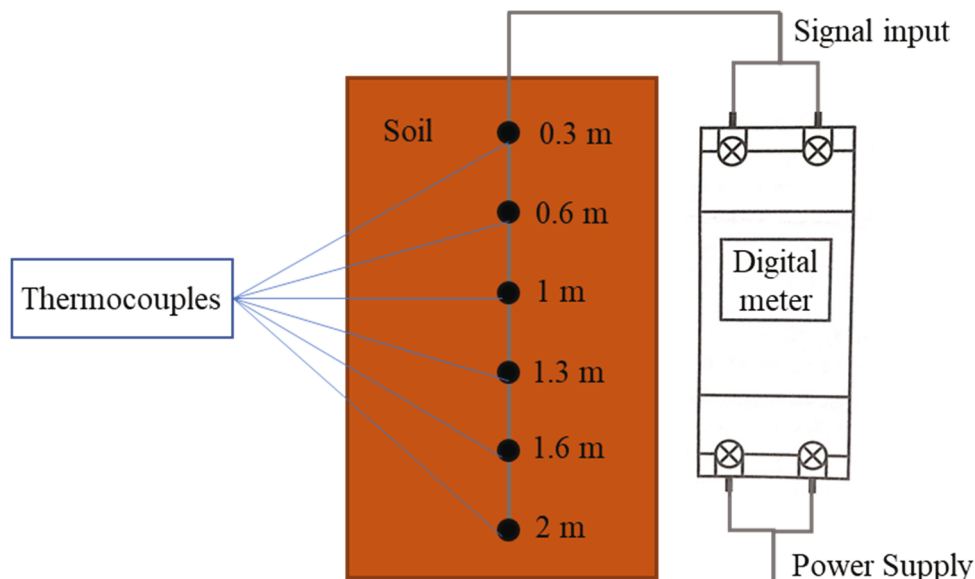


Fig. 2. Schematic of the ground temperature measuring setup.

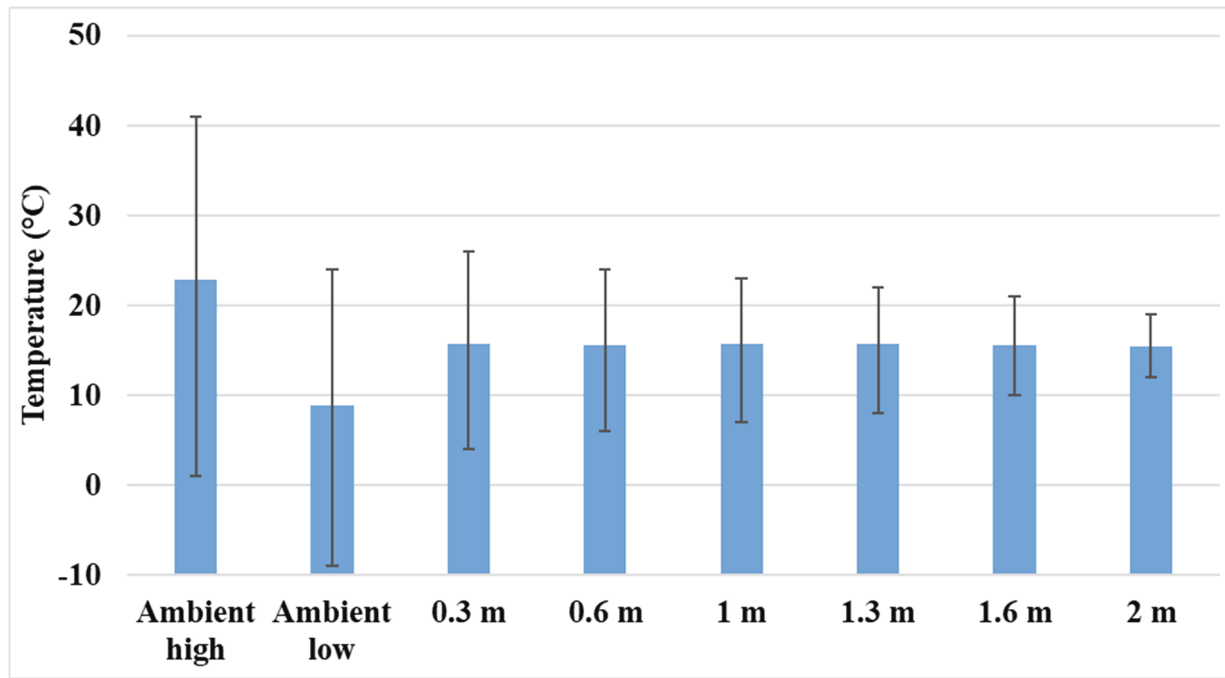


Fig. 4. The difference between ambient and ground temperatures; average, highest, lowest and temperature difference in Bekaa-Lebanon during 2020.

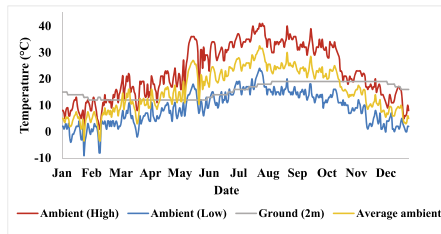


Fig. 5. The variation of ambient highest, lowest, and average temperatures in comparison with the ground temperature at 2 m depth in Bekaa-Lebanon during 2020.

that the ground temperature can be decreased using a cooling recovery strategy as will be presented in Section 5.2 to enhance the performance of ground-cooled condenser during operation. Additionally, the peak load is not only the main reason for comparing the ground temperature with that of daytime ambient average temperature, but in many applications the system does not operate at night. This will be discussed in detail in Section 5.3 showing the significance of choosing the operational duration of the proposed power cycle which is assumed to be from 06:00 to 24:00. Therefore, the upcoming sections will be based on these assumption as if the system's maximum possible operating duration is 18 h/days.

4. Effective cooling source temperature

The aim of this section is to manage the operation of each condenser according to the lowest available temperature. This is essential because the aim of using a ground-cooled condenser is to decrease the condensation temperature in the Rankine power cycle knowing that this parameter is directly proportional to the cooling source temperature. As will be discussed in Section 5.2, a hybrid-cooled condenser is used and composed of GHE and air/water-cooled heat rejector such that they utilize the ground and ambient air as cooling sources, respectively. This makes it necessary to control the operation of each cooling source subsystem by comparing the ground and ambient air temperatures at

each instant during the day. This means that when the ground temperature is lower than that of ambient, the GHE will be operating, otherwise the primary heat rejector will be the only functioning heat exchanger.

4.1. Operating cases

In this section, the ambient air temperature is assumed to be varying linearly during the day such that the lowest and highest ambient air temperatures are at 06:00 and 13:00, respectively. The equations and algorithm were coded into Visual Basic within Excel and used to carry out the simulation to estimate the value of daily effective cooling source temperature.

4.1.1. Case 1: Ground temperature is less than the lowest ambient temperature

This case occurs in summer when the ambient temperature is greater than that of ground during the entire day. Fig. 6 presents a representation of case 1 such that the ground temperature horizontal line is always lower than that of ambient. In this case, the effective cooling source temperature during this day will be equal to that of the ground. This means that the GHE has the potential to operate from 06:00 to 24:00. However, this does not mean that the other heat rejector is not operating (see Section 5.2). The primary heat rejector can remain functioning to reduce the heat rejected to the ground avoiding heat accumulation. In addition, the air/water cooled heat exchanger has an important role in such days since it will be running at night to ensure providing coolth

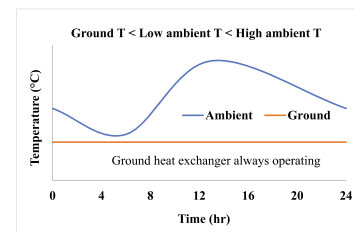


Fig. 6. Ground cooling system operating the entire day (case 1).

compensation.

4.1.2. Case 2: Ground temperature is higher than the highest ambient temperature

During winter, the ground temperature can be always higher than that of ambient air in some days as shown in Figs. 3 and 5 (mainly in January, February, and December). In such cases, it is needless to use the ground as a secondary cooling source since it is incapable of rejecting heat from water after passing through the primary heat rejector. Case 2 is depicted in Fig. 7 in which the ground temperature at a depth of 2 m is greater than the highest ambient temperature. In this case, the condenser will be only depending on the air/water cooled heat exchanger since it is providing the lowest temperature during the entire operating duration. For this reason, the effective cooling source temperature in case 2 is equal to the average ambient temperature during operating hours. It is essential to mention that the possibility of having this case can be reduced after adopting the optimized system (see Section 5.2). Therefore, it is expected that this case will be mainly representing the days where there is a sudden drop in the ambient air temperature.

4.1.3. Case 3: The ambient temperature fluctuates around the ground temperature

This is the most complex case in which the ground temperature is lower than the highest ambient temperature while it is higher than that of lowest ambient. Fig. 8 presents case 3 showing that the highest and lowest ambient temperatures are recorded at 06:00 and 13:00. As shown in Fig. 3, this is the most frequently occurring case in the year 2020. Assuming that the ambient temperature is varying linearly during the day, the equation of a straight line is used to represent the temperature as shown in Eq. (1). The temperature function can be divided into two parts such that it is increasing during 06:00–13:00 and decreasing during 13:00–24:00. Thus, it is necessary to find the equations of these lines in terms of highest and lowest ambient, and ground temperatures to calculate the daily effective cooling source temperature based on the ground cooling system (GCS) operating duration.

$$T = at + b \quad (1)$$

where T , a , t , and b are the temperature, slope, time, and y-intercept.

Eq. (2) shows the first intersection point between the ground and ambient temperatures.

$$t_1 = \frac{7(T_g - T_{min})}{T_{max} - T_{min}} + 6 \quad (2)$$

where T_{max} and T_{min} are the highest and lowest ambient temperatures during the day at 13:00 and 06:00, respectively. t_1 is the starting operation time of GCS and T_g is the ground temperature at a depth of 2 m. (Note: the value of t_1 must be between 06:00 and 13:00).

To calculate the approximate temperature at 24:00, the temperature is assumed to be decreasing linearly from 13:00 to the next day at 06:00. Therefore, if the temperature is decreasing at a constant rate, the temperature at 24:00 can be calculated as shown in Eq. (3).

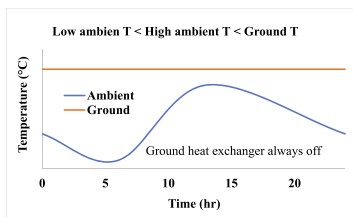


Fig. 7. Ground cooling system not operating (case 2).

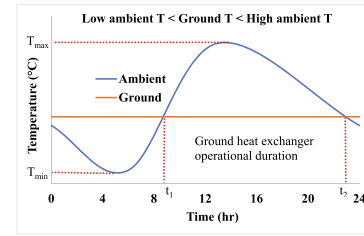


Fig. 8. Ground cooling system partially operating (case 3).

$$T@24:00 = \frac{6(T_{max} - T_{min})}{17} + T_{min} \quad (3)$$

Eq. (4) shows the second intersection point between the ground and ambient temperatures:

$$t_2 = \frac{17(T_{max} - T_g)}{T_{max} - T_{min}} + 13 \quad (4)$$

where t_2 corresponds to the second point of intersection between the ground and ambient temperature which is the time when the GCS is turned off. (Note: the value of t_2 must be between 13:00 and 24:00).

Fig. 9 presents the effective cooling source temperature based on the model used for case 3 in which it shows that the GHE limits the increase in ambient temperature during the daytime. Eq. (5) is used to calculate the average effective cooling source temperature during the days of case 3. For this reason, the area under the curve of Fig. 9 is divided into three areas to apply easily the integration shown in Eq. (5). The area is divided into two trapezoids and one rectangle. Thus, Eq. (6) can be considered as a representation of the final approximate average temperature. (Note: this temperature must always be between the ground and lowest ambient temperatures).

$$T_{avg,eff} = \frac{\int_{t=6}^{t=24} T dt}{18} \quad (5)$$

$$T_{avg,eff} = \frac{(T_g + T_{min})(t_1 - 6) + 2T_g(t_2 - t_1) + (T_g + T@24:00)(24 - t_2)}{36} \quad (6)$$

4.2. Ambient vs. Effective average temperatures

It is very important to calculate the daily average cooling source temperature since it directly affects the condensation temperature of working fluid. These temperatures have the same fluctuations during the year which is due to that they have a constant temperature difference (condenser's pinch temperature difference). Fig. 10 shows the difference between average ambient and effective cooling source temperatures during 2020. The average ambient temperature is calculated considering the operating hours only (06:00–24:00) while that of effective is based on the cases presented in Section 4.1. The results show that there

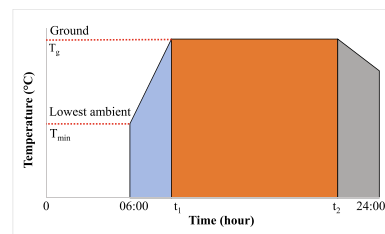


Fig. 9. The effective cooling source temperature during a day representing case 3.

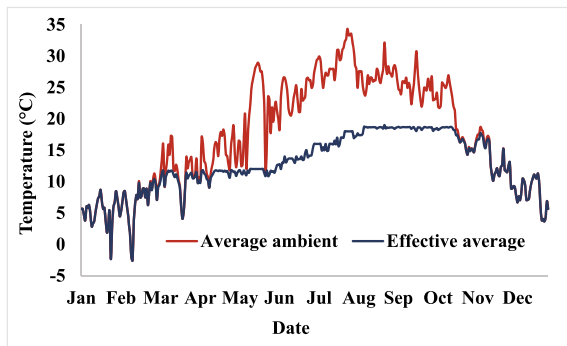


Fig. 10. The variation of average ambient and effective cooling source temperatures in Bekaa-Lebanon during 2020.

is a significant difference between the two average temperatures and especially during summer. This confirms the contribution of ground cooling source to decrease the condensation temperature of the cycle. In some days of the year, the curves coincide representing case 2 where the ground temperature is always higher than that of ambient. In addition, the difference between the two curves almost represents the operating duration of the GCS.

4.3. Ground cooling system operation

This section aims to present the daily and annual GCS operating durations. The maximum possible operating duration per day is assumed to be 18 h (06:00 to 24:00). Thus, when the GCS can operate 18 h, it will be reported as full operation (100%/day). Fig. 11 shows the variation in the daily operating potential of GHE during 2020. It presents a great potential since the average operating duration is approximately 10 h which represents 55.56% of the total operating time.

The results presented above have shown that the ground source can immensely decrease the condensation temperature of the power cycle. This is not only noticed from the difference between the temperatures, but also because the GCS can operate for long durations with large portions of the total operating time. Table 1 presents a detailed comparison between the ground and ambient sources regarding their differences in terms of temperatures and operations.

According to the operating cases presented in Section 4.1, the GCS can be fully operating, partially operating, or turned off during the daytime. These possible operations refer to the cases 1, 2 and 3, respectively. Fig. 12 shows the number of days for each case such that the GCS can be operating 258 days/year. However, 51 days of them correspond to full operations (18 h/day). It is expected that the GCS can be turned off for 107 days/year, but it is essential to mention that the operating days can be more than 258 after adopting the optimized system (see Section 5.2). Even though, the GCS is not operating during these 107 days, it is very important to take advantage of the cold

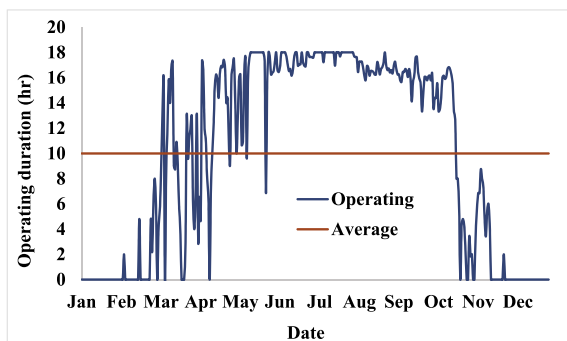


Fig. 11. The estimated annual operating hours of ground cooling system.

Table 1

The difference between the effect of ground and ambient cooling sources on the proposed system; operations and temperatures.

Ground cooling system operation	Value	Unit
Maximum operating duration	18 (1 0 0)	hours/day (%)
Average operating duration	~10 (55.56)	hours/day (%)
Full operation (18 h/day)	51 (13.97)	days/year (%)
Total operation (0–18 h/day)	258 (70.68%)	days/year (%)
Maximum difference with highest ambient temperature	24	°C
Maximum difference with lowest ambient temperature	22	°C
Average difference with highest ambient temperature	7.33	°C
Average difference with lowest ambient temperature	6.64	°C

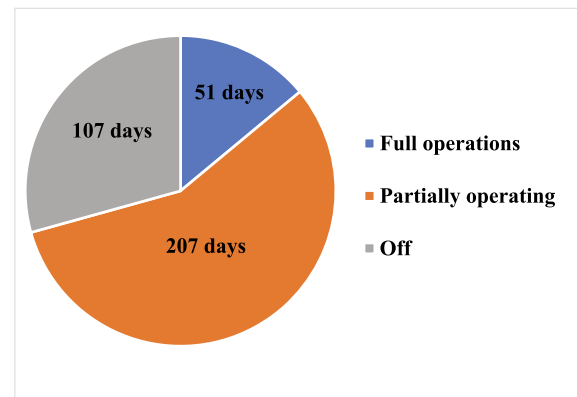


Fig. 12. Summary of the potential of using a ground cooling system in Bekaa-Lebanon.

ambient air in winter to recover the ground's coolth energy. This allows the ground source cooling system to operate more than 258 days/year considering the decrease in ground's temperature due to the additional heat rejection provided by the primary heat exchanger.

5. Parametric study for system optimization

This section presents the methodology that is followed to optimize the power generation system incorporating a ground-cooled condenser, displayed in Fig. 1. However, in this section, the ground heat exchanger is placed in soil considering the absence of shallow underground water in many regions (ex: Bekaa-Lebanon). System optimization also aims to mitigate the negative effects of critical parameters such as pressure drop, low mass flow rate and large ground loops. This requires the investigation of different configurations and working fluids to ascertain their effects on the performance of the system. The purpose of system optimization is to help increase the net output power whilst reducing the capital cost of installation (thermodynamic and economic aspects). Fig. 13 presents the flow chart diagram displaying the optimization approach. The first part aims to compare two different possible ground cooling system's configurations based on the pressure drop inside the ground loop. After that, the operating modes will be presented depending on the cases displayed in Section 4.1.

5.1. Direct cooling vs. Indirect cooling

The system depicted in Fig. 1 shows the ground-cooled condenser concept exhibiting a direct cooling method. This means that a direct

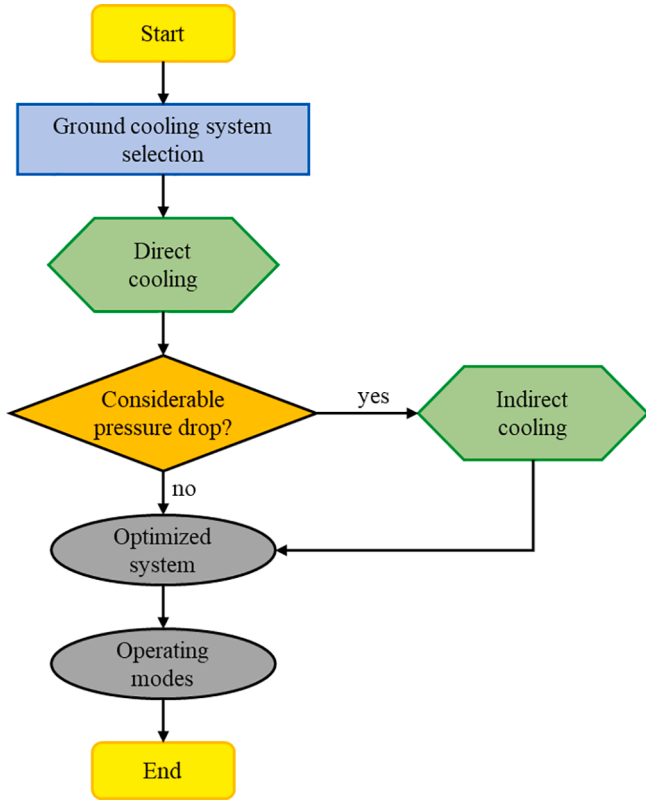


Fig. 13. A flow chart diagram representing the methodology used in the current study.

contact between the cooling source and power cycle is available. This method is usually used to produce the highest amount of power since no intermediate loops are involved (minimum pinch temperature can be assumed). However, this may be accompanied by severe pressure drops in the condenser and hence negatively affecting the overall system's performance. This is also more considerable in the absence of underground water when large ground loop is required. In most cases, the ground loop is installed in the soil as shown in Fig. 14. The main concept of using shallow horizontal ground-cooled condenser as direct and indirect cooling systems is presented in Fig. 14a and b, respectively.

5.1.1. Effect of pressure drop

This section aims to investigate the effect of pressure drop in the direct ground cooling system (see Fig. 14a) to check if it is feasible to use such a strategy or it is better to add an intermediate loop to make the system more controllable and avoid the corresponding negative impacts.

5.1.2. Theory of modelling

The model used in this study is developed in Engineering Equation Solver (EES). The thermodynamic performance of the cycle depends mainly on the gas and power cycle's conditions (mass flow rate, temperatures, and pressures). The net output power can be calculated by:

$$\dot{W}_{net} = \dot{W}_t \cdot \eta_{ge} - \dot{W}_p - \Delta P \cdot Q \quad (7)$$

where $\dot{W}_t$ is the turbine power, η_{ge} is the generator efficiency, $\dot{W}_p$ is the pump power, ΔP is the pressure drop, and Q is the volumetric flow rate. $\dot{W}_t$ and $\dot{W}_p$ mainly depend on the mass flow rate of the working fluid and the enthalpy variation as shown in equations (8) and (9).

$$\dot{W}_t = \dot{m}_f (h_1 - h_2) \quad (8)$$

$$\dot{W}_p = \dot{m}_f (h_4 - h_3) \quad (9)$$

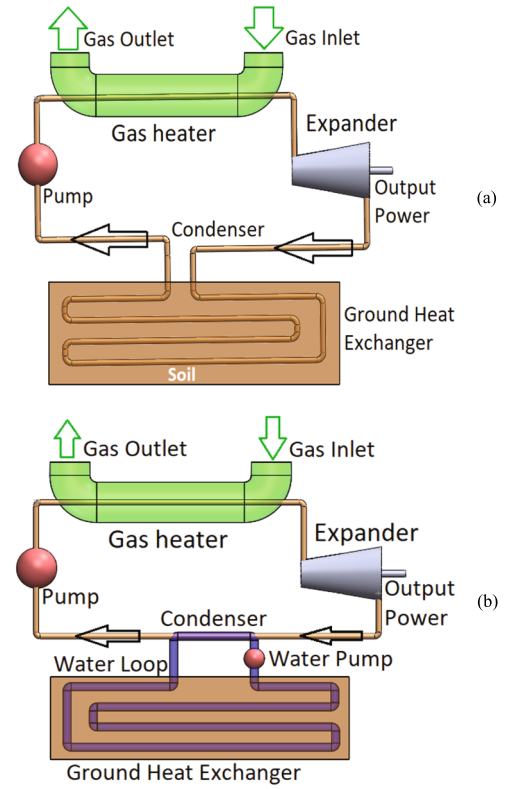


Fig. 14. (a) Direct and (b) indirect ground cooling systems.

Eqs. (10) and (11) show the method used to ascertain the pressure drop effect [41]. This method is considered for turbulent flow in smooth pipes with values of Reynold's number ranging between 4000 and 10^5 .

$$f = \frac{0.316}{Re^{0.25}} \quad (10)$$

$$\Delta P = \frac{\rho \cdot f \cdot L \cdot v^2}{2D} \quad (11)$$

where f , Re , ΔP , ρ , L , v and D are friction coefficient, Reynold's number, pressure drop, density, length, velocity, and diameter, respectively. The working fluid's velocity is calculated as shown in Eq. (12).

$$v = \frac{4\dot{m}}{\rho \cdot \pi D^2} \quad (12)$$

Table 2 presents a summary of the conditions used for investigating the effect of pressure drop. These parameters are either fixed at the values mentioned in the table or will be varied and reported later during

Table 2

Parameters considered for investigating the effect of pressure drop.

Parameters (Units)	Values
Gas heater diameter (mm)	40
Gas mass flow rate (kg/h)	300
Gas inlet temperature (°C)	777
Gas outlet temperature (°C)	120
Expander inlet pressure (MPa)	15
Expander inlet temperature (°C)	500
Ground temperature (°C)	15
Condensation temperature (°C)	25
Cycle pipe diameter (mm)	10
Expander isentropic efficiency	0.7
Pump isentropic efficiency	0.8
Generator efficiency	0.9

the simulations. According to a study carried out by Fujii et al. [42], it is recommended to keep the installed horizontal pipes 2 m apart to avoid thermal interference between them. This means that the effect of each pipe could reach 1 m. For this reason, in this section, the soil thermal interference is assumed to be 1 m. In other words, the ground temperature is assumed to be constant at 1 m far from the GHE. The working fluid considered in this study is the same as that used in the reference system, i.e., CO₂-based transcritical Rankine cycle [37]. The cycle was used as a heat recovery system at the exhaust of an engine based on the study done by Shu et al. [43]. The exhaust gas was formed of 19.84% CO₂, 8.26% H₂O and 71.49% N₂. In the current work, the generator's efficiency was given a constant value of 90% which can be considered as an approximation same as that used in Ref. [43]. However, the generator's efficiency depends on the expander inlet and outlet temperatures.

6. Methodology

The methodology that was followed to develop the presented model is as follows:

- Entering the heat source characteristics: composition, specific heat, thermal conductivity, viscosity, and Prandtl number.
- Choosing the condensation and evaporating temperatures based on the ground and heat source temperatures, respectively.
- Evaluating the enthalpy of working fluid at all states.
- Calculating the working fluid's mass flow rate.
- Dividing the heat exchangers (evaporator and condenser) into two parts to separate the change of phase and temperature investigations.
- Determining the working fluid's characteristics based on the average temperature in the two parts of heat exchangers: Reynolds number, Nusselt number, Prandtl number, viscosity, thermal conductivity, and convection heat transfer coefficient.
- Calculating the heat transfer coefficient of heating and cooling sources.
- Calculating the overall heat transfer coefficient (U) to evaluate the required size for both heat exchangers [37].
- Evaluating the pressure drop inside the heat exchangers.
- Calculating the cycle's net output power as shown in Eq. (7).

7. Results and discussion

In this section, the simulations are carried out to compare three models with minor differences; ideal direct ground cooling (I-DGC), considering pressure drop in the condenser (C-DGC) and considering pressure drop in both heat exchangers (DGC). The effect of pressure drop can be represented by the difference in net output power between the mentioned cases.

Fig. 15 shows that the net output power is significantly affected by the cycle's pipe diameter. This is especially noticed at small pipe diameters (below 15 mm). However, the minimum value of diameter can also change depending on the grade of energy source since it was increased from ~13 to ~16 mm when the mass flow rate of gas increased from 200 to 300 kg/h. From this point of view, it can be reported that the negative effect of pressure drop can be avoided, but this depends on the available gas conditions and equipment cost that may be changed when large diameters are required.

To further study the effect of energy grade source on the pressure drop consideration, the gas temperature and mass flow rate were varied from 700 to 1500 °C and 100 to 300 kg/h, respectively as shown in Fig. 16. It can be noticed that the curves corresponding to the ideal case are diverging, while those of DGC are converging. This confirms that the pressure drop is relatively more considerable for higher grade energy sources. This shows that the pressure loss is increasingly affected by the amount of heat added to the cycle. The pressure drop in both heat exchangers is almost the same which can be determined from the rate of change between the three presented models. The main reason causing

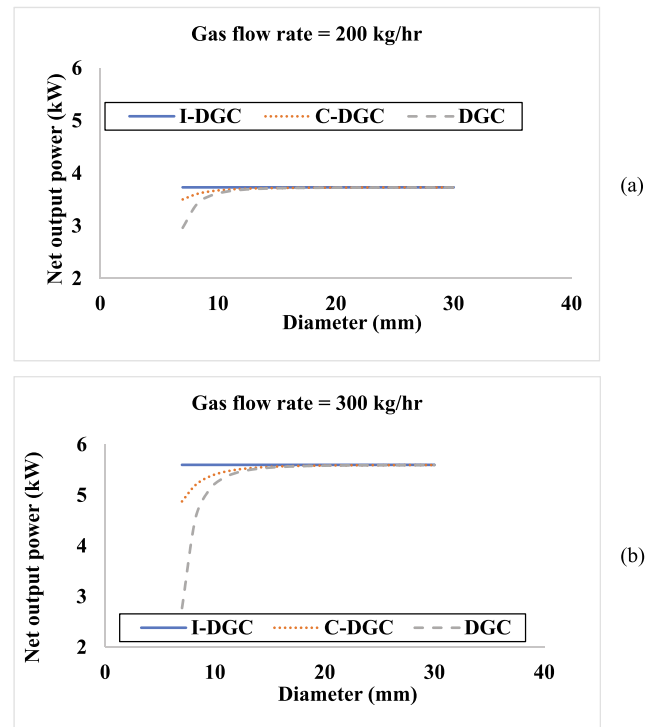


Fig. 15. The effect of cycle's pipe diameter on the pressure loss at gas mass flow rates of (a) 200 kg/h and (b) 300 kg/h.

the pressure loss effect to increase with the grade of energy is the increase of working fluid's mass flow rate. As shown in Eq. (5.2), the pressure drop is highly affected by the fluid's velocity knowing that the latter and mass flow rate and directly proportional at a given cross-sectional area.

It may appear good in some cases to change the conditions of the cycle to optimize the system and achieve the best operating conditions. However, this is an ineffective method to avoid the negative impacts accompanied by pressure drop. This can be noticed from the results presented in Fig. 17 since the change in expander inlet temperature and pressure did not significantly affect the discrepancy between the studied models. Even though the net output power difference between the three considerations was decreased at high temperatures and pressures, this requires a considerable change in the conditions which is usually unacceptable.

The results presented in this section show that the effect of pressure drop cannot be neglected and will indeed cause significant drawbacks and change in cycle conditions. Thus, it would be recommended to introduce an intermediate water loop between the cycle and ground to ensure stability, make the system more controllable and avoid critical issues. This encourages using the indirect cooling strategy presented in Fig. 14b. However, this system needs to be further modified to avoid a large ground loop installation. It is also important to mention that an antifreeze liquid must be mixed with water to avoid freezing since the cooling source temperature can decrease below 0 °C as presented in Fig. 10.

7.1. Optimized system

The heat rejected from a power cycle can be relatively massive with respect to the shallow GHE capacity, otherwise a large installation would be required. This causes additional expense making this system inappropriate for such utilizations. For this reason, it is better to integrate another cooling source into the hybrid power cycle such as air-cooled or water-cooled heat exchanger to operate as a primary heat rejector. Another advantage of this integration is to provide coolth

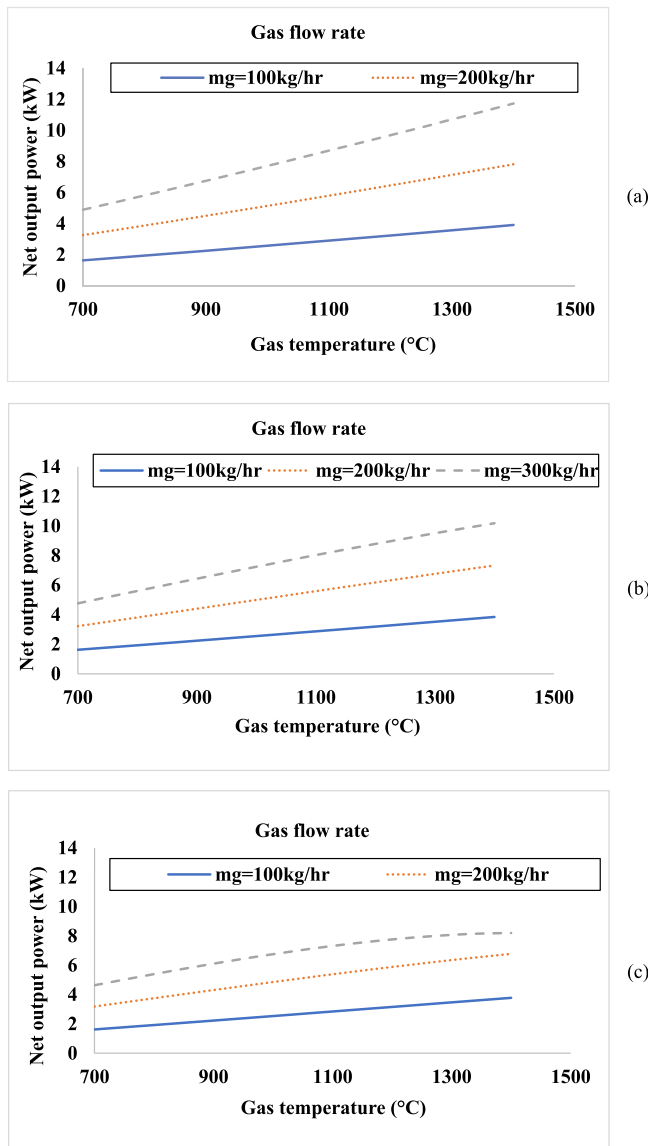


Fig. 16. Effect of energy grade source on the net output power of (a) I-DGC, (b) C-DGC and (c) DGC.

compensation to the GHE in which this can immensely enhance its performance during operating hours. This recovery system can operate during the night whilst the ORC is off such that only the water loop will be running to transfer heat from the ground to the ambient air. However, it is recommended to introduce an underground storage medium that has high thermal conductivity and storage capacity, such as composite phase change materials, to allow the surrounding around the GHE to store coolth energy. This contributes to compensating the cooling ability of the ground source as well as improving the overall heat transfer coefficient to increase the heat transfer rate between the ground and circulating coolant.

The optimized system is presented in Fig. 18 in which the two types of heat exchangers are connected in series. A bypass line is connected in parallel with the GHE to avoid exchanging heat with the ground when the ambient temperature is lower than that of the ground. On the other hand, the primary heat rejector will be always operating to reduce the amount of heat rejected from the cycle to the ground preventing heat accumulation and the need for large GHE installations. Therefore, a directional control valve (DCV) is used at the exit of primary heat rejector (state 6) to control the flow path of water; either passing through the GHE or overtaking it to directly enter the circulating pump.

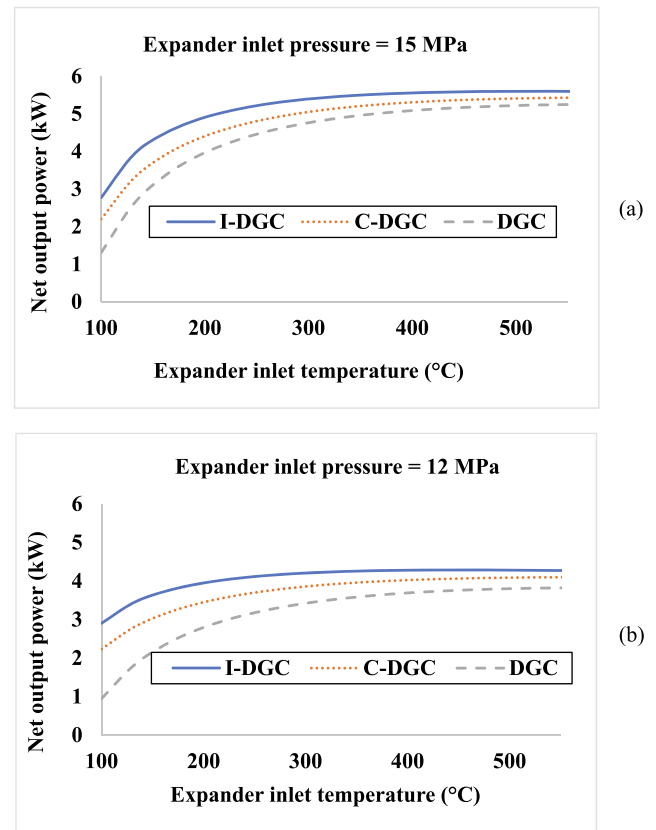


Fig. 17. The influence of expander inlet conditions on the effect of pressure drops at (a) 15 MPa and (b) 12 MPa.

Another DCV is placed at state 8 to allow bypassing the cycle's condenser at night when the system is operating under recovery cooling mode. Thus, the two bypass lines help the ground to recover its coolth energy by decreasing its temperature when the power cycle is off (mainly at night) by extracting heat from the ground to the ambient air. It is also necessary to use a DCV at the inlet of primary heat rejector which helps overtaking this heat exchanger when the water exiting the condenser is below than that of ambient air (state 5).

The optimized system can be further enhanced by utilizing the heat rejected from the cycle between states 5 and 6 to increase the overall system's efficiency. This can maximize the output of the system by providing two types of outputs: electricity from the Rankine cycle and heat from the water loop. A large portion of heat is rejected from the water loop by the air/water-cooled heat exchanger, and this can be used to heat domestic water or utilized as an input to a heating system during winter months. Another possible utilization is the preheating of water prior to entering an electrolyzer. This can be helpful in producing hydrogen knowing that this type of combination suits the proposed system well since the electrolysis process requires both available forms of energy, electrical and thermal. It is also possible to use a regenerator which is a heat exchanger used to transfer the heat remaining in the working fluid when exiting the expander to that entering the gas heater. This can also reduce the required heat input for producing the same amount of power or increase the net output power while maintaining constant heat addition.

7.2. Operating modes

This section aims to manage the operation of the optimized system presented in Fig. 18. The DCVs placed at states 5, 6 and 8 are responsible for controlling the flow paths of the intermediate water loop, while the water pump helps regulating the amount of heat rejected from the cycle.

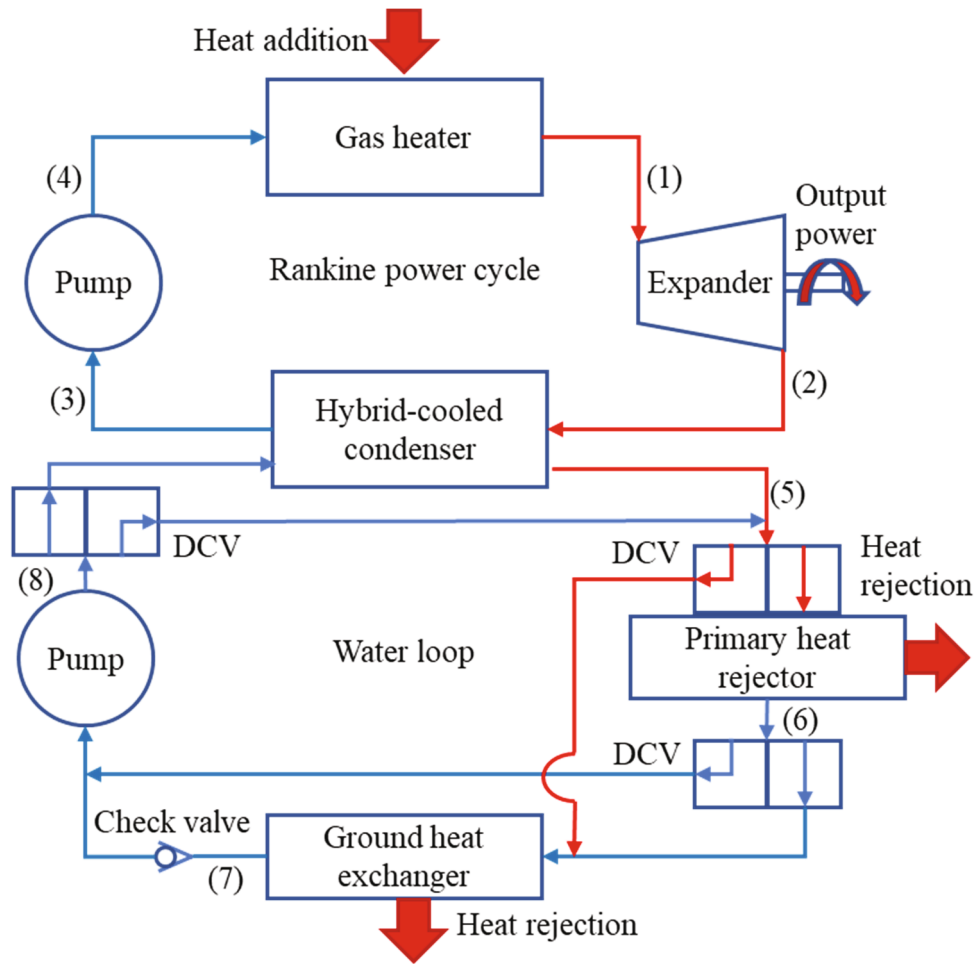


Fig. 18. Schematic diagram of the optimized system; directional control valve (DCV).

Another advantage of the latter regulation is to facilitate the ground's coolth recovery at night. Concerning the operating modes, the ORC is either turned on or off, while the water loop has four operating modes with different flowing paths.

7.2.1. Normal operation (mode 1)

This mode corresponds to the case when the ground temperature is below that of the ambient air. For this reason, the coolant exiting the primary heat rejector (state 6) passes through the GHE to further decrease its temperature. Then, cold water (state 7) is supplied to the condenser (state 8) via a circulating pump. In this mode, there is no need to use any of the bypass lines since both heat rejectors are activated. This operation is usually required during the daytime when there is electricity demand, and the power cycle is turned on. However, it is essential to ensure that the ambient temperature during this mode is higher than that of the ground, otherwise the coolant entering the GHE will gain heat instead of rejecting it.

7.2.2. Ground cooling system turned off (mode 2)

The second possible mode of operation represents the case when the ground temperature is higher than that of the ambient air. This is also needed only when the power cycle is turned on, otherwise mode 4 will operate. The ground's temperature can be relatively high mainly in two cases, either in winter or due to high loads leading to heat accumulation. Thus, it is necessary to connect thermal sensors to allow regulatory control of the operating modes. The thermocouples must be placed very near to the GHE to detect the increase in effective ground's temperature and compare it with that of ambient. This regulation can significantly

affect the cycle's performance since it helps to select the suitable operating mode (1 or 2).

7.2.3. Primary heat rejector turned off (mode 3)

In some summer days, the ambient air cannot be used to extract any amount of heat from the water loop due to the low water temperature exiting the condenser compared to that of ambient. In this case, it is better to bypass the primary heat rejector. Hot water directly enters the ground loop to decrease its temperature. In this mode, the ground cooling system (GCS) is operating at full load and the ground is receiving the highest amount of heat compared to other operating modes. In these periods, mode 4 is very essential during night hours to ensure coolth compensation because the condenser is only depending on the GCS during the daytime.

7.2.4. Coolth recovery (mode 4)

In this mode, the power cycle is turned off while water is only circulating in the primary heat rejector and GHE. This operation contributes to decreasing the ground's temperature by recovering its coolth energy. It helps to maintain low condensation temperatures and avoid ground heat accumulation. This mode is mainly used at night when the ground temperature is higher than that of ambient. However, it can also be used during off-periods in some days of winter as presented in Section 4.1. This operational mode shows the importance of integrating ground thermal energy storage technologies into the proposed optimized system. This means that introducing storage material in the form of grout can store coolth energy during night hours to increase the heat rejection capacity of the ground cooling system. This decreases the effective

cooling source temperature during operation.

8. Conclusions

The ground and ambient temperatures were measured in Bekaa-Lebanon during 2020 and a detailed comparison was provided. The thermocouples were inserted at depths of 0.3, 0.6, 1, 1.3, 1.6 and 2 m. All ground temperatures were more stable than that of ambient air such that as the depth increased the stability increased. The maximum differences between highest and lowest temperatures during 2020 were 40 °C, 33 °C and 7 °C for ambient high, ambient low and ground temperature at 2 m, respectively. The corresponding average values were 22.83 °C, 8.87 °C and 15.51 °C. Three different operating cases were presented based on the difference between ground and ambient air temperatures in each day. According to these cases, the ground cooling system significantly decreased the average effective cooling source temperature. The ground cooling system can operate 207 days/year with full operations of 51 days. This was based on the potential of operating between 06:00 and 24:00 in which this was considered as the maximum duration since the ORC is always turned off during night hours. An intermediate water loop was added between the power cycle and GHE to avoid the negative effects of pressure drop. This was considered as indirect cooling strategy and mainly used to ensure stability and make the system more controllable. The condenser was further upgraded to a hybrid-cooled condenser which was based on ground and air/water heat exchangers. The latter was introduced as a primary heat rejector to reduce the amount of heat rejected to the ground and provide coolth compensation during off-periods.

As for future work, the system can be further enhanced using a regenerator or investigating different types of working fluids. It is also necessary to study the economic feasibility of the proposed system by introducing it to a specific application. It would be recommended to integrate it into low-grade energy sources since it is expected that the proposed approach will have more influence on such systems. It is worth investigating more parameters that may affect the system's performance such as the ground soil thermal properties, soil type, water content, wind speed and rain fall. Additionally, the effect of cycle's conditions on the efficiency of components can be further studied to display more accurate results such as the generator and expander efficiencies.

CRedit authorship contribution statement

Montaser Mahmoud: Writing – original draft, Investigation, Writing – review & editing, Visualization. **Mohammad Alkhdher:** Writing – review & editing, Visualization. **Mohamad Ramadan:** Conceptualization, Writing – review & editing, Visualization, Supervision, Project administration. **Keith Pullen:** Writing – review & editing, Visualization, Supervision. **Abdul-Ghani Olabi:** Writing – review & editing, Visualization, Supervision. **Sumsun Naher:** Writing – review & editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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