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Modification of an Organic Rankine Cycle (ORC) for Green Energy Management in Data Centres

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Abstract Silicon Carbide (SiC) was integrated into an Organic Rankine cycle (ORC) design to enhance its ability to operate at high temperature. Low-grade heat dissipated from large data centres was used to run the modified ORC to generate electrical power. This allowed for a temperature increase of low-grade heat to a temperature capable of improving the power output and efficiency of the turbine used in the ORC. This research demonstrated that energy management can be applied in large centres, 65 MW power can be generated from a 260 MW data centre at a temperature of 150°C and mass flow rate of 476.19 kg/sec. Heat pumps were integrated into the ORC system to boost the temperature of heat rejected from the condenser and making it available for the cycle. Temperature values from 135°C - 270°C were used to optimise the best temperature to achieve a maximum power production in the ORC; 157.5°C showed a maximum output power of 65 MW. A 25% electrical power can be produced from low-grade heat dissipated by data centres by using modified ORC provided the inlet and outlet enthalpies are constant for all data centres.

Keywords: *data centres, Organic Rankine Cycle (ORC), waste-heat, low-grade heat, energy efficiency, energy management, Silicon Carbide (SiC)*

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1. Introduction

Data centres are a major consumer of energy; the large energy consumption of data centres has contributed to global warming because of the heat that is constantly dissipated. The heat is usually given off to the environment. This heat dissipated can be regarded as energy that is constantly wasted by data centres. The heat given off from data centres can be termed low grade because the temperature at which this heat is given off is not a high one. Therefore, it is essential to seek a solution to the dissipated heat from data centres rather than leaving it to waste.

Data centres consume a lot of energy and the workload of data centres is very high; this also contributes to high-energy consumption and a high cost of electricity [1,2]. The energy consumed by data centres poses a challenge to power utility companies because they need more infrastructures to help meet the demands of data centres. Also, the electricity generated to power these data centres are derived from carbon-intensive fuels such as coal, crude oil and natural gas that pollutes the environment [2]. Due to these growing concerns, green energy was introduced to help power data centres and this gave rise to green data centres. This comes with some challenges because most of the data centres introduced renewable energy sources like solar, wind, etc. and these renewable sources are intermittent. Since energy consumption is a growing concern for data centres, popular IT companies like Google, Yahoo and Facebook have taken a step ahead of the other IT companies to introduce renewable energy in their data centres to reduce their reliance on fossil fuels which reduces the overall electricity cost and carbon emissions [1,3]. For instance, Facebook has a data centre in, Oregon, USA which is powered by solar [1] and in addition to this solar-powered data centre of Facebook, it also has another data centre in Wyoming that is powered using wind energy [1].

One major challenge of renewable energy sources is that this energy is intermittent; the availability of renewable energy sources is not guaranteed at all times. For example, the availability of solar energy is dependent on the sun i.e. Solar energy is not available on a rainy or cloudy day and at night, likewise wind energy; wind energy is only available on windy days except it is stored for future use. Different methods have been employed to reduce the impact of these intermittencies [2,4]. To solve this problem, the green energy could be stored up in batteries or on the power grid; a better approach is to match energy demand to the supply [2].

Due to the large power consumption of data centres and losses associated with its operation, some studies [5,6,7] have investigated the ways to recover heat dissipated in data centres. "Heat is a form of energy that is transferred across the boundary of a system at a given temperature to another system (or the surroundings) at a lower temperature by virtue of the temperature difference between the two systems" [8]. This means that heat dissipated by the servers in data centres is transferred from those servers at a higher temperature to the system supplying chilled air at a lower temperature. Heat transfer takes place mainly because of the difference in temperature between the two systems (servers and chillers).

A research carried out by Bell Labs showed how waste-heat can be harvested using thermoelectric modules (TEMs) [9]. There is a direct conversion of waste-heat to electricity using the thermoelectric effect present in TEMs. Bell Labs used thermoelectric effect to recover heat ejected from their communication systems. The thermoelectric module is coupled to the vapour chamber; vapour chamber increases the efficiency because heat coverage is over a larger surface area of the thermoelectric module [9]. The goal of Bell labs was to use this method to recover at least 10% of the energy that is used to power their communication equipment [9].

Another research [5] used recovered heat from data centres to cool down the data centre itself and also to supply cooling to the servers. To achieve this, a heat recovery system was designed to recover the heat dissipated by data centres, and its thermal energy was used to produce hot water; the hot water was transferred to the Lithium Bromide water solution present in an absorption chiller to aid its boiling which would eventually make it produce cool air to the building.

The low-grade heat from data centres was converted to electrical power by using one of the thermodynamic power cycles called Organic Rankine Cycle (ORC). ORC is capable of using a low temperature of waste heat to produce power.

An ORC is recommended over a Rankine cycle for waste heat recovery system because it has a lower boiling point compared to water which means power can be produced even at a low temperature and this will make the cycle efficiency better. An ORC is best suited because an organic working fluid is used such as hydrocarbons, refrigerants and Carbon dioxide [10]. This fluid boils at a temperature lower than water and it also has a lower freezing point lower than water.

This paper focuses on the heat constantly dissipated from data centres and the heat could be termed as low-grade. The low-grade heat from data centres is converted to electrical power by using one of the thermodynamic power cycles called ORC. ORC is capable of using the low temperature of waste heat to produce power. A modified ORC was proposed in this paper that makes use of Silicon Carbide in its power supply. With the modified ORC presented in this paper, the low-temperature waste from data centres could be increased as high as 200 °C without the power supply breaking down due to the high operating temperature of Silicon Carbide. Also, the boosted temperature would improve the efficiency of the cycle, thereby producing more electrical power.

Most research works focused on how to reduce data centres reliance on fossil fuels by making use renewable energy sources like solar, water and wind [1,11,12]. This paper focuses on how to recover the waste produced from data centres because there is always an output even with the use of fossil fuels or renewable energy; heat is always given off as waste in data centres. This waste heat is then used to drive an ORC to produce power rather than releasing the heat to the environment. Therefore, this research aims to maximise the thermal energy produced as waste in data centres by using it to drive a revised model of an ORC.

2. Materials and Methods

2.1. Organic Rankine Cycle Using Silicon Carbide

A simple system that can be used to recover the low-grade heat from data centres was designed using an ORC as shown in Figure 1. The electrical power consumed by data centres is equivalent to the heat dissipated from the data centre. The ORC in Figure 1 uses thermal energy derived from the waste heat from data centres to run the ORC; the steam produced in the evaporator is used to turn the blades of the turbine to produce electrical power. The modified ORC design in Figure 1 was assumed to use a refrigerant called Pentafluoropropane (HFC-245fa) as its working fluid with a low boiling point at 15℃ and it is non-flammable. This ORC is powered using the heat from data centres which means, an estimate needs to be done to know how much power the pump would need to function in the ORC. Also, the mass of fluid passing through the cycle was estimated per unit time.

Since the heat is of a low grade, a means was devised to increase the temperature; a heat pump was introduced into the ORC to increase the temperature of the fluid before it goes into the evaporator and finally to the steam turbine where the thermal energy is converted into electrical energy to produce power; if an attempt is made to increase the temperature of the fluid beyond the limit the power supply can withstand, it could cause damage to the power supply; therefore, a semiconductor that is capable of withstanding high-temperature changes was introduced into the system. Silicon Carbide was used in the power supply because it can operate at high temperature because of its wide-band gap of 3.3eV and a high thermal conductivity of 5 W/cmK. Therefore, Silicon Carbide would enable a high-temperature fluid to pass through the entire process of the cycle without the system breaking down; this also made variations of temperatures above 180°C to be tested on the ORC. SiC semiconductor was introduced into the system because of its ability to withstand high temperature and it can perform well even in high voltage of about 100kV [13].

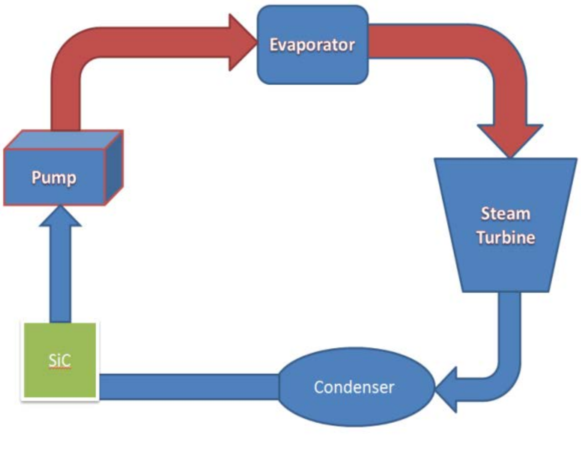

Figure 1. A modified Organic Rankine Cycle

The wide band of SiC makes it possible to withstand and operate in high temperatures of above 400°C [13,14]. It was realised that putting this in the power supply for the ORC would make it possible for the ORC to withstand the high-temperature level without damage to the power supply.

The size of a data centre determines how much power could be recovered from it and various data centre sizes were used for this power recovery estimation. The estimation of data centre size used in this paper ranged from 50 MW to 260 MW.

The electrical power that a steam turbine can produce from the dissipated energy derived from data centres was calculated using,

$$Pdc = Mf \times C \times \Delta T \tag{1}$$

$$Mf = Pdc / \left(C \times \Delta T \right) \tag{2}$$

Where Pdc is the power equivalent to the waste heat given off by a data centre, Mf is the Mass Flow Rate, C is specific heat capacity of water expelled from the condenser and ΔT is the temperature difference of the water before and after SiC has increased the temperature. The initial temperature was assumed to be 200°C and it comes out of the condenser at 60°C, then heat pump was used to raise the temperature to 1500°C. The specific heat capacity of water is 4.2 J/g°C and Pdc is assumed to be 280 MW. Therefore, using equation (2),

The Mass Flow Rate, Mf = 1.7ML

27280 litres/hour was assumed for the flow rate of the pump required which means 63 pumps ((1714285.728 litres/hour)/(27280 litres/hour)) would be required for a flow rate of 476.19 kg/sec. Also, the power of the pump power was estimated by making an assumption of 1 kW for each pump, this means 63 pumps will consume 63 kW for a 1714285.728 litres/hour operating at 130°C and this 1 kW pump needed could be purchased easily from any electrical store. The high-pressure water from the pump is directed to the evaporator where it is converted to steam.

2.2. Power Delivered by Turbine from Heat Recovery Process

The power delivered by the turbine was estimated using the following parameters:

Mass flow rate (m_f), inlet specific enthalpy of fluid (h_{inlet}), outlet specific enthalpy of fluid (h_{outlet}) and work done by turbine per unit mass (w_t).

The first law of thermodynamics shows how impossible it is to destroy or create energy; instead, the energy can be changed to various forms. The energy possessed by a system may be changed by heat transfer, by applying work to the system or by the addition/removal of elements present in the system [15].

The first law of thermodynamics was applied to the ORC in Figure 1 to calculate the internal energy of the turbine as given in equation (3) and (4).

$$Q = 0 = h_{inlet} - h_{outlet} + W_t \tag{3}$$

Therefore, the work done by the turbine is given by:

$$W_t - h_{inlet} - h_{outlet} \tag{4}$$

The specific enthalpy of the steam entering and exiting the turbine was calculated using a steam table. Enthalpy is the internal energy possessed by a fluid and this is measured in Joules or British Thermal Unit (BTU) or in calories. A steam table was used to know the properties of the steam at the inlet and outlet of the turbine. The temperature of the fluid entering into the turbine was estimated to be 150°C and the temperature of the fluid rejected from the turbine was estimated to be 60°C.

The specific enthalpy of steam that corresponds with the temperature of 150°C was noted as the h_{inlet} and that of 60°C was noted as h_{outlet}.

From the steam table, the specific enthalpy of the fluid entering into the turbine (h_{inlet}) at 150°C is 2746 kJ/kg and the specific enthalpy of steam discharged from the turbine (h_{outlet}) at 60°C is 2610 kJ/kg. The work done by the turbine was also calculated using the equation given in (4). The work done by the turbine is the difference between the inlet and outlet specific enthalpy of the fluid, w_t = 136 kJ/kg.

The power delivered by the turbine (P_t) was determined using,

$$\begin{aligned} P_t &= Mf \left(h_{inlet} - h_{outlet} \right) \\ &= MfW_t \\ &= 65\ MW \end{aligned}$$

Therefore, the power delivered by a 260 MW data centre using the ORC in Figure 1 is approximately 65 MW. A graph of the calculated efficiency against power consumption of data centres was generated as shown in Figure 2.

3. Results and Discussion

3.1. The Isentropic Characteristics of the Pump and Turbine

According to the second law of thermodynamics, which states “it is impossible to take heat from a system and convert it into work without simultaneous changes occurring in the system or in its environment” [16] can be used to explain the results shown in Figure 2. Heat transfer in the ORC caused changes in temperature as it moved from a hot region to a warm or cool region. The heat made available from the data centre is what was converted to thermal energy, then to mechanical energy that was used to turn the blades of the turbine to produce electrical power at the output of the turbine.

Regardless of the size of the data centre, the ORC had a constant efficiency as shown in Figure 2. The efficiency remained constant for all other data centre sizes because the temperature change was constant for all the data centres (i.e. the temperature of the waste heat dissipated; an efficiency of 25% was achieved despite the variation of the power output from data centres. The effect of SiC on the temperature was assumed to be the same for all the data centres) and the temperature change of 130°C remained constant throughout the process and as a result, there was no entropy change in the pump. For instance, the pump and turbine in the ORC have constant entropy because they both worked in a close loop and had a constant mass flow rate. The mass flow rate was calculated for each data centre and the mass was not changed throughout the process despite the energy conversion that occurred in the turbine. In conclusion, it could be said that the pump and turbine exhibit isentropic characteristics.

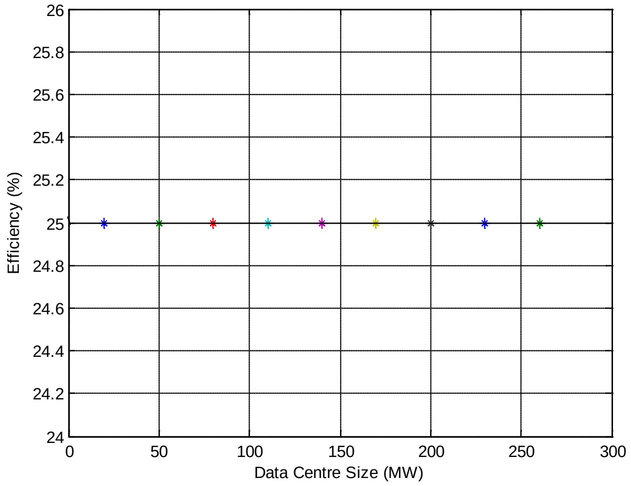

Figure 2. Graph showing the efficiency of the ORC with the power consumption of DC

3.2. The Effect of Mass Flow Rate on Power Recovered

The power output from the data centre affected the mass flow rate, from Figure 3 it was seen that the size of a data centre had an effect on the mass flow rate. It can be said from Figure 3 that the bigger the size of a data centre, the larger the mass flow rate and more power would be recovered from a large data centre as shown in Figure 3.

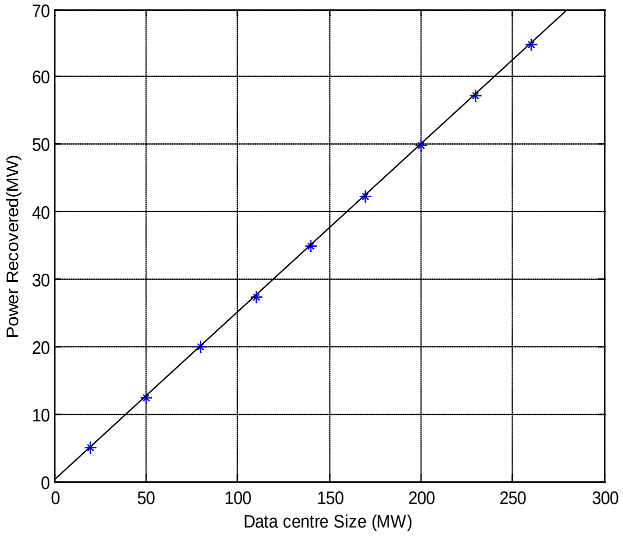

Figure 3. Graph showing power recovered from various data centres

From the calculations and as illustrated in Figure 3, it was observed that a 260 MW data centre had a mass flow rate of 476.19 kg/sec; while 80 MW data centre had a mass flow rate of 146.52 kg/sec. This is because a large data centre would dissipate more heat than a small data centre with lower heat dissipation. The graph in Figure 3 shows that power recovered from data centres is directly proportional to the size of the data centre. The slope of the line of Figure 3 when calculated resulted in 0.25.

Also, a large data centre would most likely house more servers than a small size. As a result, these large data centres would consume more power and dissipate a large amount of heat. Therefore, the mass of hot water entering the pump would be more than that from a small data centre, and this would affect the mass flow rate. This means more power can be recovered from large data centres as shown in Figure 3; power recovered from the data centres were calculated and it showed 65 MW as the power recovered from a 260 MW using ORC, whereas 42 MW was recovered from a 170 MW data centre. It was assumed that the nine data centres represented in Figure 2 and Figure 3 all operated with an inlet temperature of 150°C and an outlet temperature of 60°C.

3.3. Effect of Inlet Specific Enthalpy on the Recovered Power

The temperature of steam entering the turbine determines how well the turbine would function. From Figure 4, it was noticed that an increase in the inlet temperature brought about an increase in the specific enthalpy of steam that was used to turn the turbine to produce power; a corresponding increase in efficiency and power delivered by the turbine was observed provided mass flow rate is kept constant.

A data centre size of 260 MW having a mass flow rate of 476.19 kg/sec was assumed. The inlet temperature was increased from 150°C to 225°C at an increment of 15°C and the inlet enthalpy was used to observe how a temperature increase would affect the work done by the turbine. A graph showing the relationship between the inlet specific enthalpy of fluid and inlet temperature was plotted as shown in Figure 4.

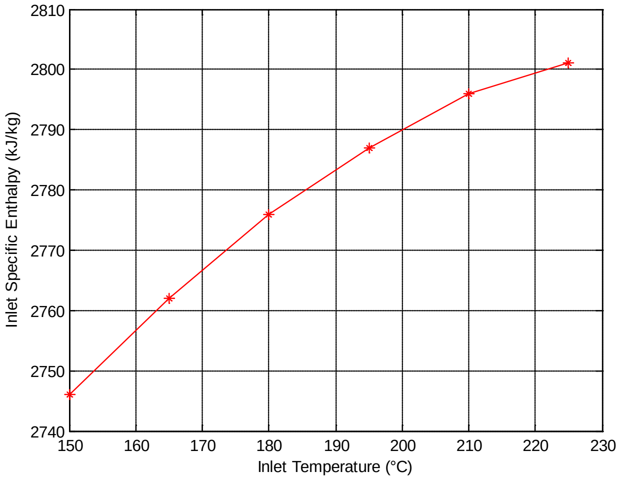

Figure 4. Inlet Specific Enthalpy of Fluid against its Temperature

It can be seen from Figure 4 that the work done by the turbine was increased whenever the specific enthalpy of steam was increased, and this made the turbine to produce more power. It could be deduced that an increase in the specific enthalpy of steam would increase the power output of the turbine because power generated by the turbine is affected by the enthalpy and mass flow rate. Also, the efficiency of the turbine will increase with an increase in steam inlet temperature. From Figure 4, an inlet temperature of 150°C will have an enthalpy of 2746 kJ/kg (this value can be read directly from a steam table) and 64.74 MW power was produced, and this made the turbine to have an efficiency of 25%. Whereas an inlet temperature of 225°C will have an enthalpy of 2801 kJ/kg, 90.95 MW power was produced making the turbine efficiency to rise to 35% as shown in Figure 5.

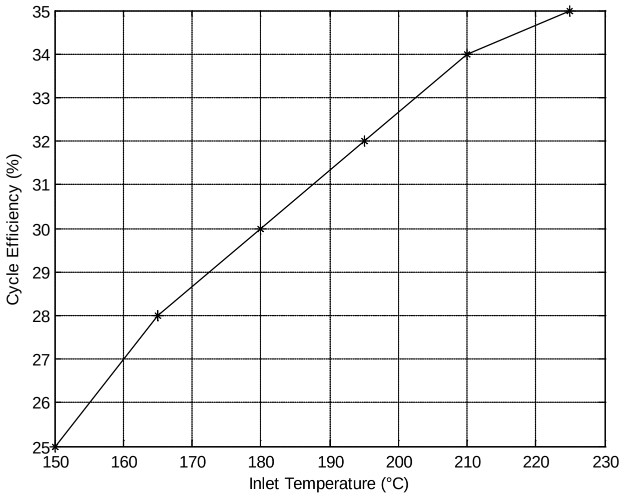

Figure 5. Turbine Efficiency versus Steam Inlet Temperature

3.4. Variations in Silicon Carbide Temperature

The source heat temperature (low-grade heat from data centres) was varied and different temperature values were assumed by making use of SiC with high-temperature values. The temperature was increased gradually from 150°C to 270°C using 15°C increment to observe how temperature increase would affect the power produced by the turbine as illustrated in Figure 6.

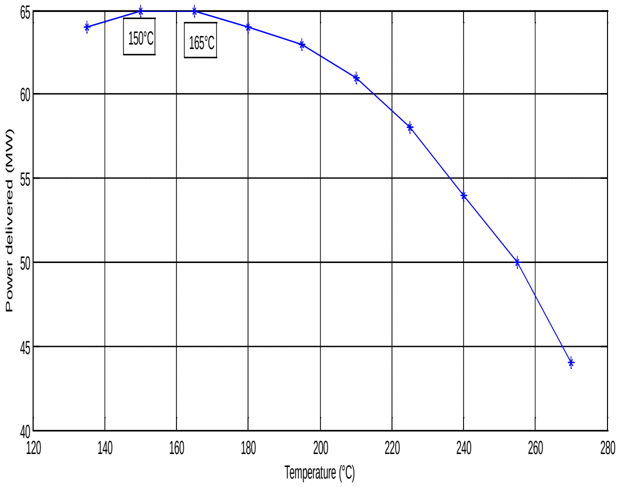

Figure 6. Temperature Variation on the Power delivered by the turbine

Increasing the temperature would increase the specific enthalpy of steam as discussed earlier in section 4.3. From Figure 6, it was observed that 150°C and 165°C gave the highest power output and an average of both temperature values gave 157.5°C. Therefore, the highest power can be produced at 157.5°C. This means temperatures below 150°C or above 165°C would reduce the power produced by the turbine. At 150°C and 165°C, 65 MW power was produced, but there was a decline in the power delivered by the turbine as the temperature was increased from 165°C upwards. From Figure 6, it could be said that power production by the ORC in Figure 1 would decline if the fluid temperature is above 165°C.

3.5. Recovery of Condensation Heat using Heat Pump

The condenser in the ORC takes in the flow ejected by the turbine. The flow enters the condenser at low pressure and temperature unlike when it entered the turbine at high pressure and temperature. A phase change occurred at the condenser and as a result, steam is changed to its liquid state. Heat is rejected from the condenser during this phase transformation. The heat from the condenser is usually blown away, but the heat blown away could be seen as a waste of energy.

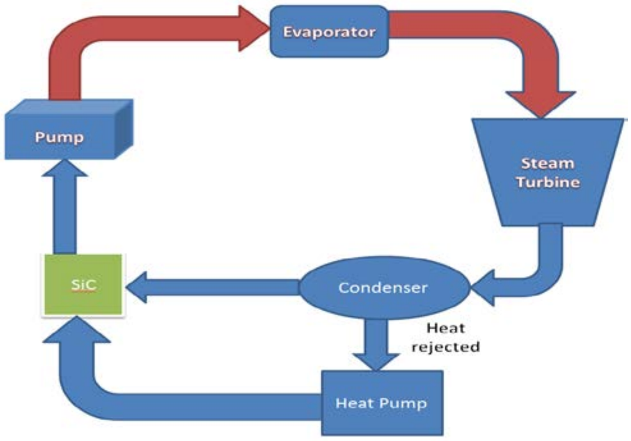

Figure 7. Heat Recovery from Condenser Using Heat Pump

Since this research is concerned about green energy management systems, it is of paramount importance that the heat from the condenser is fed back into the ORC system as shown in Figure 7. A heat pump was integrated into the ORC to collect the heat being expelled from the condenser. The heat pump raises the temperature of the condenser heat before it moves to the pump, evaporator, and turbine and back to the condenser then to the heat pump; this process will continue in this closed loop.

4. Conclusion

A modified ORC was used to recover low-grade heat dissipated from data centres. The heat from data centres is usually blown away to the environment and this contributes to global warming. Therefore, the low-grade was used to run Organic Rankine to produce power. Also, a heat pump was added to the cycle to capture the heat that is usually ejected from condensers during the process of phase change (vapour to liquid). Thermodynamic principles were applied to calculate the heat recovery process of an ORC. SiC was added to the system; SiC has a wide band gap from 2.3eV to 3.4eV and this gives it the ability to operate at high temperature and it has a high thermal conductivity of 5 W/cmK.

Calculations were based on large data centres within the range of 20 MW - 260 MW to examine how much power could be produced using the heat dissipated to run the ORC depicted in Figure 1. A temperature change of 130°C, turbine inlet temperature of 150°C and turbine outlet temperature of 60°C were assumed to calculate the mass flow rate for each data centre.

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