# Pre-assessment of a low-temperature geothermal and solar ORC system for power co-generation: the Effi low res approach

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*Abstract:* - Under the auspices of Effi low res project an ORC power generation unit working at low temperatures with improved overall efficiency will be developed. The performance of the ORC unit that will exploit low temperature energy sources (solar and geothermal) will be optimized so as to make it cost effective. The research focuses on the preliminary design of the ORC apparatus giving technical specifications that comprises working fluid selection, sizing of solar plant, heat exchangers and expanders and other auxiliary equipment. Modeling techniques have been applied to study the performance of refrigerants selected for the specific application so as to justify the selection of the most suitable refrigerant for process optimization. As it is shown R134a as a working fluid is an optimal solution based on the balance of three factors studied: required amount of heat, mass flow rate and cost.

*Key-Words: ORC, geothermal energy, solar energy, refrigerant*

## 1 Introduction

Renewable energy sources, such as solar thermal and geothermal energy are potentially energy sources that are capable to meet electricity demand. However, the moderate temperature heat from these sources cannot be converted efficiently to electrical power when using conventional power generation methods. For that reason and for the conversion of low-grade heat sources into electricity various cycles have been proposed [1-3] as the organic Rankine Cycle (ORC), supercritical Rankine cycle, Kalina cycle, etc. The literature shows extensive analyses and comparisons among different thermodynamic cycles and working fluids [1-15]. However, most of the comparisons were conducted under certain predefined temperature conditions and used only a few working fluids [4–15]. As ORC is much less complex and need less maintenance it is a promising process for conversion of low and medium temperature heat to electricity.

In Greece, there are areas with water sources with temperature higher than 80$^{o}$C [16]. Also, classic solar thermal systems with flat solar collectors may produce temperature around or more than 80$^{o}$C. Both cases have been exploited for various uses mainly for space heating, greenhouse heating etc or other thermal uses [17]. The exploitation period of such systems is limited in periods with thermal needs, namely periods where these systems (especially the solar thermal systems) show decreased performance and present increased losses. However, the period that the above heats are available is during the whole year while they are maximized during summer where thermal needs are limited. For the improvement of the performance and exploitability of those applications during the whole year various technologies have been developed, the main one among them is cooling production technology or/and power generation with a relatively low efficiency especially at temperatures around or up to 80$^{o}$C.

The Effi Low Res project intends to develop an ORC power generation unit working at low temperatures with improved overall efficiency by exploiting low temperature sources so as to make it cost effective. The ORC applies the principle of Rankine cycle steam but uses an organic fluid with a low boiling point to recover the heat from low temperature heat sources. The choice of refrigerant for a given application is a key to its successful implementation [1-15] as it plays a major role in the cycle. A working fluid must not only have the necessary thermo-physical properties that match the application but also possess adequate chemical stability in the desired temperature range.

The current study refers to the preliminary design of the ORC apparatus giving technical specifications that comprises working fluid selection, sizing of solar plant, heat exchangers and expanders and other auxiliary equipment.

## 2 The Effi Low Res project

The current work focuses on the design and modeling of an experimental apparatus of a low-temperature geothermal and solar ORC system for electrical power generation. The apparatus will be manufactured and installed at two pilot sites in Greece. The one ORC will be powered by low enthalpy geothermal well and the second one by solar collectors.

### 2.1 Geothermal

The electrical power generation plant proposed in the current work from low enthalpy geothermal well, will be installed at Lesvos island, Greece, in the Polichnitos area [16], utilizing the heat of an existing geothermal field as shown in Fig. 1.

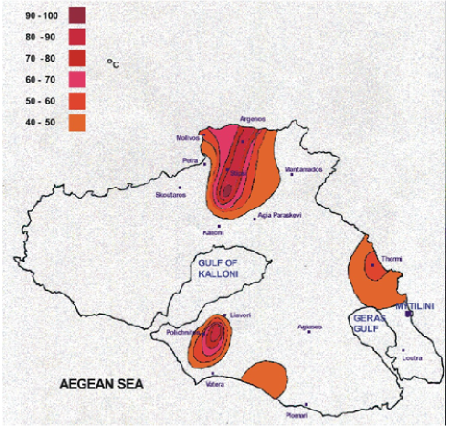

Fig.1 Isocontours of geothermal field in Lesvos island, Greece.

Lesvos is located in the northeastern Aegean Sea and is mainly characterized by its Miocene volcanism [16]. In the southeastern part of the island and close to the Gulf of Geras, there are outcrops of an ophiolite basement. Alluvial deposits have been formed along the Gulfs of Kalloni and Geras [18]. Geothermal exploration of the island began in the late 1960s; it included geological mapping, thermal manifestation surveys, geochemical investigations, drilling of and temperature measurements in shallow wells. There are hot (50–85 ◦C) springs (Fig.2) near the seashore in the northern and southeastern parts of Lesvos and inland of the Gulf of Kalloni [16,19].

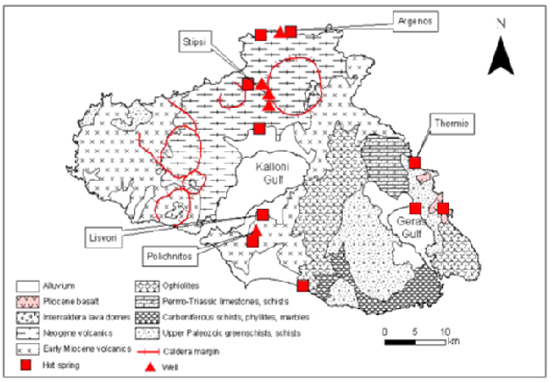

Fig.2 Geologic map of Lesvos Island showing the location of hot springs and thermal wells [16].

Polichnitos has been recognized as an area with high temperature geothermal field that is used for district heating [19,20]. The thermal energy to be used for the present application of electrical generation from an ORC plant is derived from the geothermal well at Polychnitos (Table 1). This geothermal field feeds the existing district heating system that has been constructed under the auspices of the THERMOPOLIS project (Table 1). In the area of the drilling a small hutch has been built that comprises engine room for production and injection wells, plate heat exchanger with titanium heat transfer plates, switchgear and other heat metering and electrical consumption devices and recirculation pumping for warmed water available to consumers.

Table 1 Technical specifications of Polichnitos geothermal production well.

| area [km$^2$] | Reservoir depth [m] | flow rate [t/h] | Tmax [°C] | TDS [g/kg] | Fluid type | (maturity indice |
|---|---|---|---|---|---|---|
| 10 | 50-200 | 400 | 92 | 12 | Cl | <2 |

The geothermal fluid yields thermal energy by the geothermal well in a temperature of approximately 85$^o$C, through an intermediate Plate Heat Exchanger to the evaporator of the ORC that operates with refrigerant R134a (Fig. 3). From the existing drilling, the geothermal fluid will be pumped in a temperature of approximately ~85$^o$C, with a productivity of 35m$^3$/h at a depth of 150m. Table 2 shows technical characteristics of the geothermal heat exchanger and calculated annual results.

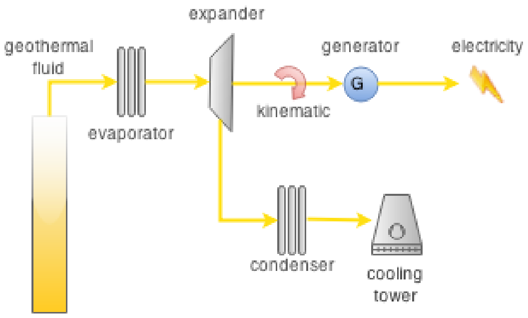

Fig.3 Energy flow diagram for geothermal ORC system.

Table 2 Technical characteristics of the geothermal heat exchanger and annual results.

| | **Geothermal heat exchanger** |
|---|---|
| **Type** | Plate counter-current made of Ti |
| **Hot side fluid** | Geothermal fluid |
| **T inlet/outlet hot side** | 88/54,6°C |
| **Cold side fluid** | Water |
| **T inlet/outlet cold side** | 51,6/85°C |
| | |
| | **Annual results** |
| **Heat production from geothermal fluid** | 161.3 MWh |
| **Heat losses from hydraulic circuit** | 10% |
| **Heat to ORC** | 145.3 MWh |
| **Electricity production** | 10 MWh |
| **Cycle efficiency** | 6.89% |
| **Capacity Factor** | 97 % |

## 2.2 Solar

The solar apparatus will be installed at Central Greece University of Applied Sciences Campus in building D of Mechanical Engineering Department (Fig.4). The Campus is cited at Psachna Evias, in Central Greece.

Fig.4 Ground plan of the building at Psachna Evias Source: Google Earth

The meteorological data for the area of Psachna Evias were taken from the Meteonorm software [21], that uses irradiation data from 1986 until 2005 (Figs. 5,6). For this area, the total annual irradiation for 30° inclination and South orientation is 1914 kWh/$m^2$. Regarding the system operation, the solar collectors convert the irradiation to heat that is then transferred, through a heat exchanger, to the storage tank. The hot water inside the storage tank is then lead to a heat exchanger for the vaporization of the organic medium (R134a).

Fig.5 Daily total irradiation for horizontal level at Psachna Evias. Source: Meteonorm [21].

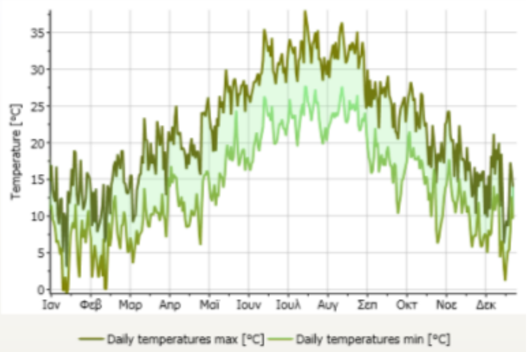

Fig.6 Daily range of dry bulb temperature at Psachna Evias. Source: Meteonorm [21].

The medium, now with high temperature and pressure is lead to a turbine and rotates it (Fig.7).

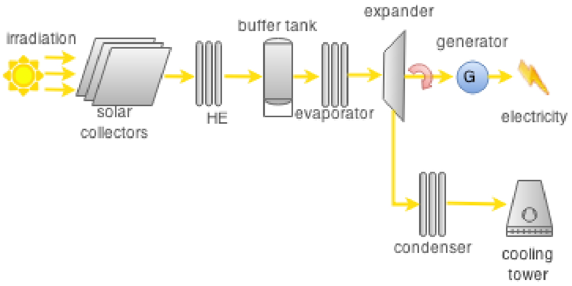

Fig.7 Energy flow diagram for solar ORC system.

The kinetic energy is transformed to electricity via the generator. The organic medium, having now lower temperature and pressure, condenses by releasing heat to the atmosphere, through a heat exchanger and an evaporative cooler. The hydraulic diagram for the proposed solar system is shown in the next figure (Fig.8).

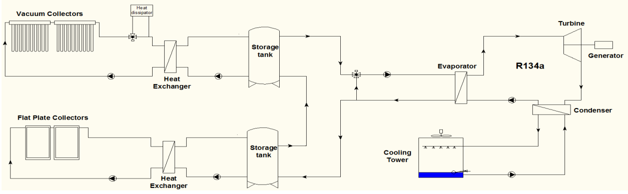

Fig. 8 Hydraulic scheme of the solar system

The solar field consists of two subsystems with different solar collector technology. The first subsystem consists of flat plate solar collectors and the second one consists of evacuated tube collectors. These two subsystems operate independently. There are also two independent heat storage tanks for each subsystem. This configuration permits a more efficient operation of the flat plate collectors and a more precise system control.

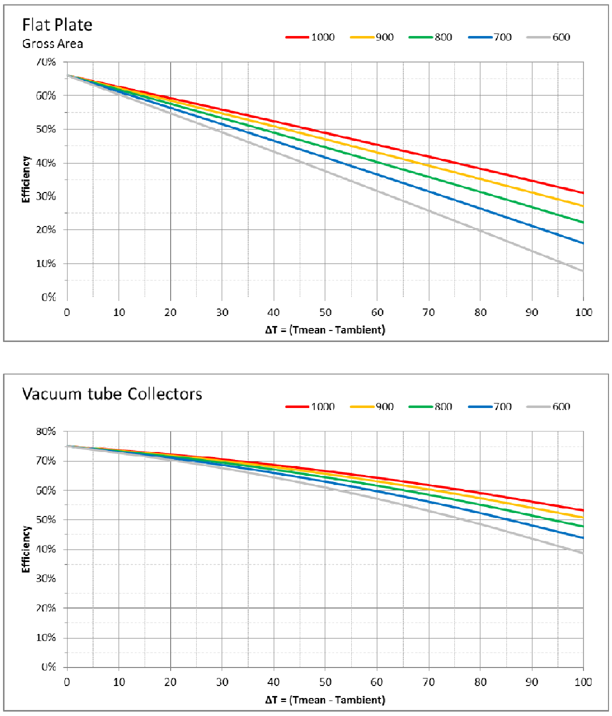

Fig.9 Comparative evaluation of the performance curves of flat plate solar collectors versus evacuated tube collectors.

In the particular electricity production system, the required collector filed comprises of 235.8 $m^2$ evacuated tube collectors and 100 $m^2$ flat plate collectors. The volume of each storage tank is 1.5 $m^3$ for the low temperature tank that uses the flat plate collectors and 3.6 $m^3$ for the high temperature tank that uses the evacuated tubes. The technical characteristics of the solar system are summarised at the following table (Table 3).

Table 3 Technical characteristics of the solar system

| | **Flat plate solar collectors** | **Evacuated tube collectors** |
|---|---|---|
| Absorber technology | Selective surface | Selective surface |
| Collectors' area | 2.5 $m^2$ | 3.23 $m^2$ |
| Number of collectors | 40 | 73 |
| Total area | 100 $m^2$ | 235.8 $m^2$ |
| Inclination / Azimuth | 30° / 0° | 30° / 0° |
| Coefficient $a_o$ | 0.67 | 0.727 |
| Coefficient $a_1$ | 3.24 $W/m^2.K$ | 1.18 $W/m^2.K$ |
| Coefficient $a_2$ | 0.017 $W/m^2.K^2$ | 0.0082 $W/m^2.K^2$ |
| **Heat storage tanks** | | |
| Volume | 1.5 $m^3$ | 3.6 $m^3$ |
| Height | 2.5 m | 2.5 m |
| Heat loss coefficient | 0.35 $W/m^2.K$ | 0.35 $W/m^2.K$ |
| **Heat exchangers** | | |
| Type | Plate, counter flow | Plate, counter flow |
| Heat capacity | 45 KW | 160 kW |
| Fluid (hot part) | Water – Glycol (30%) | Water – Glycol (30%) |
| Inlet / outlet temperature (hot part) | 75/65 °C | 85/75 °C |
| Fluid (cold part) | Water | Water |
| Inlet / outlet temperature (cold part) | 60/70 °C | 70/80 °C |
| **Heat exchangers** | **Evaporator** | **Condenser** |
| Type | Plate, counter flow | Plate, counter flow |
| Heat capacity | 200 kW | 200 kW |
| Fluid (hot part) | Water | R134a |
| Inlet / outlet temperature (hot part) | 80/ 60 °C | 35 °C gas/ 35 °C liq |
| Fluid (cold part) | R134a | Water |
| Inlet / outlet temperature (cold part) | 35 °C liq/ 75 °C gas | 27/30 °C |
| **Turbine** | | |
| Cycle efficiency | 6.3% | |
| Operating medium | R134a | |
| **Evaporative cooler** | | |
| Type | Wet cooling tower | |
| Heat rejection power | 200 kW | |
| Inlet / outlet temperature of cold water | 27/34.5 °C | |

The solar system was modelled and simulated at TRNSYS [22] which is software of dynamic simulations setting a time step of 0.2 hr.

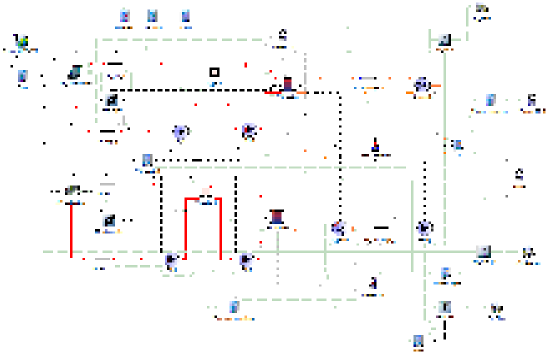

Fig.10 The solar system simulation environment in TRNSYS (Simulation studio)

The solar system produces 12.8 MWh of electricity. Having 6.3% coefficient of performance, the required energy from the solar field is 203.7 MWh. The capacity factor of the system is 34%. The annual results from the simulation of the system are shown in the table below (Table 4).

Table 4: Annual results of the simulation of the system

| Annual results | |
|---|---|
| Solar irradiation | 645 MWh |
| Solar field heat production | 237.5 MWh |
| Solar collectors heat production (both subsystems) | 834 / 397 kWh/m$^2$ |
| COP of evacuated tubes / flat plate collectors | 44% / 21% |
| Heat input to ORC | 203.7 MWh |
| COPel of solar field | 136 |
| Electricity production | 12.8 MWh |
| Cycle Efficiency | 6.3% |
| Capacity Factor | 34% |

The evacuated tube collectors operated with an annual mean coefficient of performance 44%, whereas the flat plate ones with 21%.The monthly results are shown in the graph below.

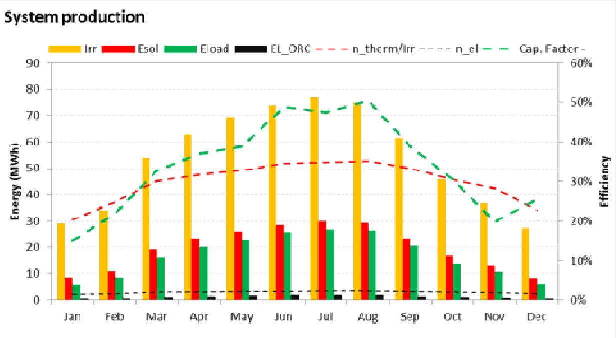

Fig.11 Monthly results of the simulation of the system

## 2.3 Selection of working fluid

System efficiency, operating conditions, environmental impact and economic viability are affected by working fluid selection. The latter must meet certain criteria such as: stability, non-fouling, non- corrosiveness, no toxicity, non-flammability, etc. The working fluid characteristics that were investigated include [3]:

1. Thermodynamic performance: efficiency and power output should be the maximum for given temperature conditions; this is usually associated with low pump consumption and high critical point.
2. Positive or isentropic vapor saturation curve. In case of positive pressure saturation curve (dry fluid) recovery exchanger may be used (recuperator) to increase the efficiency of the cycle. Negative curve leads to the formation of drops at the end of expansion [4]. The steam must be overheated at the inlet of the turbine in order to avoid destruction of the turbine, which reduces the efficiency of the cycle [5].
3. High vapor density: this parameter is important especially for fluids which show a low condensation pressure. Low density leads to large equipment at the levels of expansion and condensation.
4. Accepted pressures: high pressures usually lead to higher investment costs and increased complexity.
5. High stability temperature: in contrast to water, organic fluids usually suffer of chemical wear and decays at high temperatures. Therefore the maximum temperature is limited by the chemical stability of the fluid.
6. Low boiling point under the requirements of the project Effi Low Res.
7. Low environmental impact and high level of security: the main parameters taken into account are the Ozone Depleting Potential (ODP), the Greenhouse Warming Potential (GWP), toxicity and flammability.
8. Good commercial availability and low cost.

Refrigerant that were investigated have minimal toxicity and maintain good material compatibility and stability limits. In selecting the refrigerant for ORC with an inlet temperature of ~ 75$^{o}$C to the expander different refrigerants were studied namely R410A, R404A, HFC125, but as the critical point of their curve at p-h diagram was near the temperature of 75$^{o}$C, were discarded. Also, for refrigerants such as R407c, R32, significant overheating is required to prevent droplets in the expander, leading to a significant reduction of yield, therefore they were also discarded. Considering therefore the basic criteria of the expander inlet temperature and performance of the refrigerant cycle as well as the aforementioned environmental criteria and the availability in the market three refrigerants were selected for further investigation R134a, R245fa and HFE7000. In order to select the optimum refrigerant several simulations were conducted.

## 3 Design and simulation of Effi Low Res ORC cycle

### 3.1 ORC calculations

The ORC was calculated using the software Cycle Tempo [23] and fluid properties were based on REFPROP 9.1 [24]. The ORC modeled in Cycle-Tempo was based on the theoretical calculation of an ORC using all three selected refrigerants and was designed to produce about 10 kW of electricity. Fig. 12 shows the model of the ORC in Cycle Tempo.

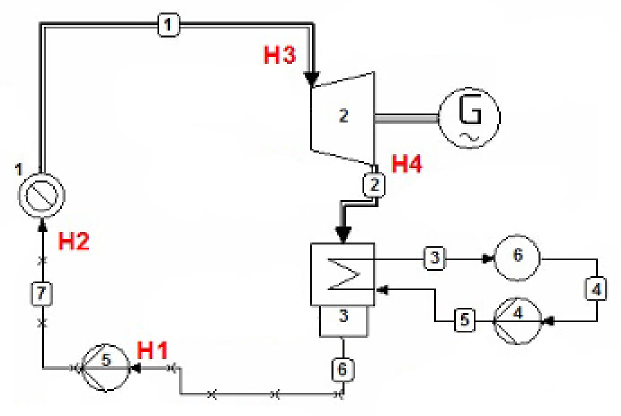

Fig.12 ORC model

The hot fluid –either from a geothermal source or from solar thermal systems- is not in direct contact with the turbine [2], but it transfers heat in a secondary circuit through the evaporator [1]. R134a vapor moves the turbine [2] which is connected with a generator producing electrical energy. Subsequently, R134a vapor is cooled, it is condensed at the condenser [3] and then through the working fluid pump [5] is guided to the evaporator [1]. For the simulation of the refrigeration cycle the following assumptions were made:

- The pressure and temperature of the heat source [1], derived from the list of RefProp for the fluid and according to the desired temperature (75°C).
- It was considered that expander [2] has isentropic efficiency (0.70) and mechanical efficiency (0.8).
- It was considered that the electrical power of the generator is 10kWe with efficiency (0.97).
- The inlet pressure in the tube [2] was derived from the list of RefProp for the fluid. As concerns the output temperature of the organic liquid at the condenser [3] it was the desired (40°C).
- In the pipe [6] as inlet condition was given that the organic fluid is 100% liquid, namely, condenser converts all organic fluid from the gaseous to the liquid state.
- Pump [5] was considered to have isentropic efficiency (1) and that it brings the organic liquid at a pressure equal to the desired. The value derived from the list of RefProp for the fluid.
- For the condenser (heat exchange equipment) the thermal power that was transferred for the cooling of the organic fluid is estimated.

The results of the simulations for a specific temperature range are presented in the following table (Table 5).

Table 5 Simulated results for the refrigerant candidates for the Effi Low Res ORC cycle.

| **R134a** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| expander 's temperat ure | | | enthalpy after expander | enthalpy before expander | enthalpy before heat source | enthlpy before refrig. Pump | enthalpy difference | | efficienc y |
| T3 | T4 | ΔT | H4 | H3 | H2 | H1 | H3-H4 | H3-H1 | [-] |
| **R134a** | | | | | | | | | |
| 75 | 40 | 35 | 419,43 | 429,03 | 257,97 | 256,41 | 9,6 | 172,62 | **5,56%** |
| **HFE7000** | | | | | | | | | |
| 75 | 40 | 35 | 397,76 | 408,75 | 249,05 | 248,81 | 10,99 | 159,94 | **6,87%** |
| **R245fa** | | | | | | | | | |
| 75 | 40 | 35 | 443,51 | 458,4 | 253,03 | 252,57 | 14,89 | 205,83 | **7,23%** |

- Under the temperature range the R245fa has the best efficiency. Specifically introduces better performance by ~1.5% than the performance of R134a and by ~0.5% better performance than the HFE7000. However, R245fa requires larger amounts for its

condensation. On average for the three fluids it is required:
R134a: 177kJ/kg HFE7000: 162kJ/kg
R245fa: 208kJ/kg

Based on the above data from the simulations it is proved that the organic R245fa is discarded due to the high required amount of heat, HFE7000 is discarded due to higher required mass flow, and R134a is selected as an optimal solution to balancing these three factors studied. R134a has the following characteristics:

- Primary, zeotropic refrigerant -CH2FCF3.
- Non-flammable and non-toxic and safer than other refrigerants on the market.
- It has no involvement in the destruction of ozone (ODP), and participation index of Greenhouse Effect (GWP) 1300.
- In addition, it presents maximum efficiency at about 75°C. For this reason and because the project concerns electricity at 80$^o$C by solar and geothermal energy, the R134a can be selected as the working fluid.
- Finally, it is available on the market, and it is used in various applications.

## 3.2 Design of experimental apparatus

In order to conduct a parametric experimental investigation of a small scale ORC, Effi Low Res participants will build and instrument a unit by adapting market parts.

A 3d drawing of the experimental unit that will be assembled is shown in Fig. 13. The experimental rig will include a range of pressure and temperature probes and it is part of a closed loop automated system that ensures that the required test parameters are controlled to within the testing tolerance specification.

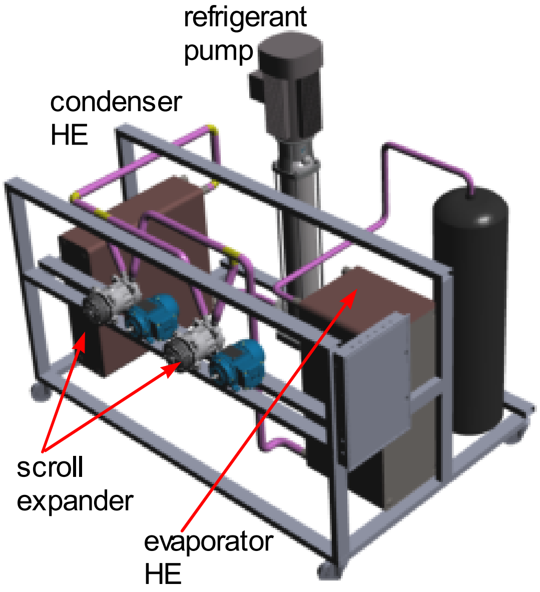

Fig.13 3d representation of ORC test rig

The evaporator and condenser are market heat exchangers (Alfa Laval). The single component that has the greatest bearing on the viability of a low temperature ORC cycle is the expander. Most commercially available turbines developed for power production purposes were designed for service with steam power plants. These units are not, however, suitable for use with many low boiling point working fluids such as hydrocarbons. Scroll type compressors lend themselves well to operating in reverse as ORC expanders [25,26]. They are mass produced leading to their cost effective application to low temperature ORC units. The Effi Low Res apparatus is designed to incorporate two (2) scroll expanders combined with electrical power generators of 5kWe each.

The generators selected are three phase two pole modern, auto-stimulated, self-regulating brushless and are manufactured according to international regulations. Finally, the working fluid pump selected was one custom-built multi stage pump with magnetic drive (Grundfos). Combined with a hermetically sealed liquid end, the pump is 100% leak free and due to the low magnetic loss is highly energy efficient.

Fig. 14 shows the type and location of each sensor on the ORC apparatus. Temperature will be recorded at the inlet and outlet at both sides of the evaporator and condenser heat exchangers and at the expander as depicted in the Figure. Pressure will be measured critical points of the working fluid network namely at the evaporator inlet, at the expander inlet and at the condenser outlet. Water

Mass flow at the condenser outlet and electrical energy production will also be measured. Measurements will be recorded every 20 sec by utilizing an advanced compact DAQ system from National Instruments.

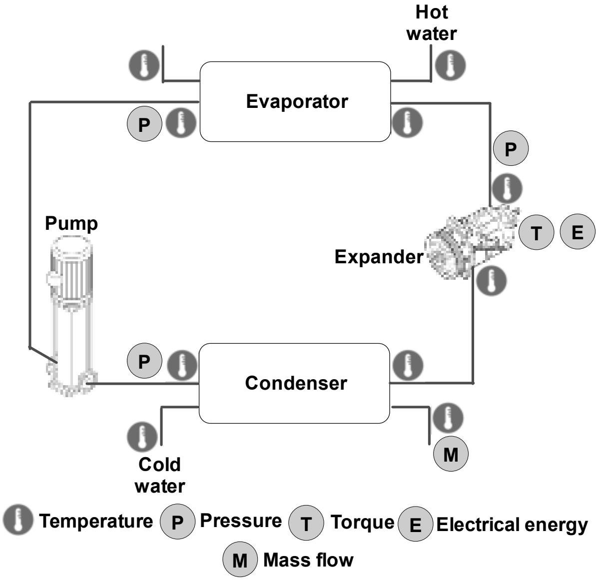

Fig.14 ORC apparatus measurement points

The instrumentation to obtain each measurement is presented the following Table 6.

Table 6 Sensors data characteristics.

| Sensor | Measurement | Accuracy |
|---|---|---|
| T-type thermocouple | Temperature | ±0.2K |
| Pressure tranducer | Pressure | ±3kPa |
| Ultrasonic mass flow | Mass flow | $\pm 0.8\text{x}10^{-4}$kg/s |
| Rotating torque sensor | Torque | ±0.07 Nm |

The control of the ORC system is vital for its high efficiency. Optimized control of the ORC involves a balance between fixed characteristics of the expander (i.e. optimal pressure ratio) and the variable heat input delivered from the low energy sources (solar, geothermal fields) . This will be achieved through a combined analog/digital control architecture that maintains the desired operating parameters via by pass control valves, pressure regulators and an inverter which control the rotational speed of the pump.

## 4 Conclusion

There is limited literature available on the cost effective mass production of ORC systems combined with low temperature heat sources. The key element for the achievement of such goal is the selection of the working fluid expander due to the trade-off between efficiency and capital cost. Also, the selection of a working fluid that achieves favourable ideal cycle efficiency is also of great impact upon the viability of these systems.

In the current work, a preliminary design study was conducted for an Efficient ORC Power Generation system with low grade energy as heat source. The results from the cycle tempo simulations showed that R134a working fluid is an optimal solution to balancing three factors studied: required amount of heat, mass flow rate and cost. Finally, scroll expander is the one selected technology because of its mass market production, cost and robustness.

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