Technical and Economical Evaluation Of Landfill-Biogas Fired Combined Cycle Plants

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ABSTRACT

Many cities are taking advantage of gas extracted from urban solid waste or USW landfills. The landfill gas is used as fuel in internal combustion engines (ICE). This is possible when the gas has been previously scrubbed and conditioned. Natural-gas-fired combined cycle plants (gas turbine, heat recovery boiler and steam turbine) can achieve overall system electrical efficiencies of 60%. On the other hand, an Organic Rankine Cycle (ORC) yields efficiencies of 10-20% by using low temperature heat sources, such as solar heat, turbine or ICE exhaust gas. In this context, by adding a power generator to an ORC and an ICE plant, it's possible to increase the overall power production by recovering 5-10% of the fuel energy content. This is in addition to the 35-40% power generated by the ICE. Thus, overall primary fuel-to-electricity efficiencies between 40% to 50% (based on the fuel's lower heating value or LHV) are possible, while using a "free" waste-derived fuel. In this article, we present a methodology based on heat integration for the conceptual design of landfill-gas fired combined cycle plants which integrate ICE and ORC technologies. The methodology has been applied to evaluate the repowering of landfill gas plant by retrofitting an ORC-based combined cycle into an existing biogas fired ICE plant, with a nominal output of 6 MWe, located in Monterrey, Mexico.

Keywords: Combined Cycle, Energy Planning, Landfill Biogas, Internal Combustion Engine, Organic Rankine Cycle, Pinch Method, Urban Solid Waste

INTRODUCTION

The benefits from recovering landfill can be grouped in two major categories: (1) a positive environmental impact and (2) an attractive economic return on investment.

Positive environmental impact benefits include a reduction in greenhouse gases due to the displacement of fossil fuels by biogas and the more energy efficient combined cycle plant; less power transmission and distribution losses since distributed generation is closer to the points of consumption; a more efficient land use due to proper landfill design and management to take advantage of landfill gas; a more sustainable way of processing solid waste with an emphasis in recycling reusable waste such as glass, metals, paper and plastic, thus resulting in smaller volume of mainly organic landfill ready waste –which maximizes biogas output.

The economic benefits comprehend economic development; job creation, from recovery, recycling and sales of USW, as well as from more efficient cogeneration plants; which yield higher return on investment and motivate further innovations in distributed generation technologies.

Henceforth, in order to maximize the environmental and economic benefits listed above, urban solid waste management can be optimized by using a hierarchical and sequential planning strategy [1, 2]. Such strategy comprehends the following steps:

Step 1: Eliminate or minimize the production of waste at the source.

Step 2: Reuse materials at the source whenever possible

Step 3: Recover all materials suitable for recycling. This entails presorting and waste collection at the source.

Step 4: Evaluate and sort the energy content or "fuel value" of all organic materials which can't be reused recovered or recycled.

Step 5: A reduced volume of mainly organic waste suitable for biogas production is placed in the landfill.

Note an evaluation of the USW energy content is needed to understand the potential for heat [3] and power [4] production. For fuel-to-energy conversion, several proven technologies can be used with USW: incineration, pyrolysis, gasification, etc. [5]. However, since many cities already have landfills, power plants have been installed to take advantage of landfill gas as a fuel; ICE being the most frequently used technology [6].

In conventional combined cycle plants gas turbine exhaust gas passes through a heat recovery boiler to generate high pressure steam which is expanded in a steam turbine. Both gas turbine and steam turbine move generators. This allows the plant to maximize power production. So, achieving as high as 60% LHV overall system efficiency is possible [7].

In the case of an ICE fired with biogas, a combined cycle is accomplished by generating power with the ICE and then recovering the heat from its exhaust gases through an Organic Rankine Cycle (ORC). This allows a compact plant configuration which produces power in two sources: the ICE generator and the ORC generator. This concept is applicable to both new and existing ICE plants fired with landfill gas.

There are few references about the energy integration of ICE and ORC technologies and the corresponding technical and economical evaluations. Thus, this research focuses in the development of the technical and economic analysis of integrating or combining the Otto cycle of a landfill-biogas fired ICE and the Rankine Cycle of ORC.

BIOGAS FIRED ICE

The electrical efficiency of an ICE (η_{MACI}) is:

$$\eta_{ICE} = \frac{W_{ICE}}{Q_{FUEL}} \qquad (1)$$

Where:

W_{ICE}: Electrical power output from ICE driven generator (kW)
Q_{FUEL}: Biogas low heating value (kW)

Most biogas fired ICEs with rated output of 3 MWe or higher have an electrical efficiency as high as 42% (LHV) [8]. The rest of the fuel energy content is rejected to the environment through: i) the exhaust gases, ii) the cooling system (jacket coolant, oil, intercooler and radiator), y iii) engine surface radiation. Figure 1 shows a typical ICE energy balance.

In biogas fired ICEs the exhaust gas temperature (T1) is 370-500°C.

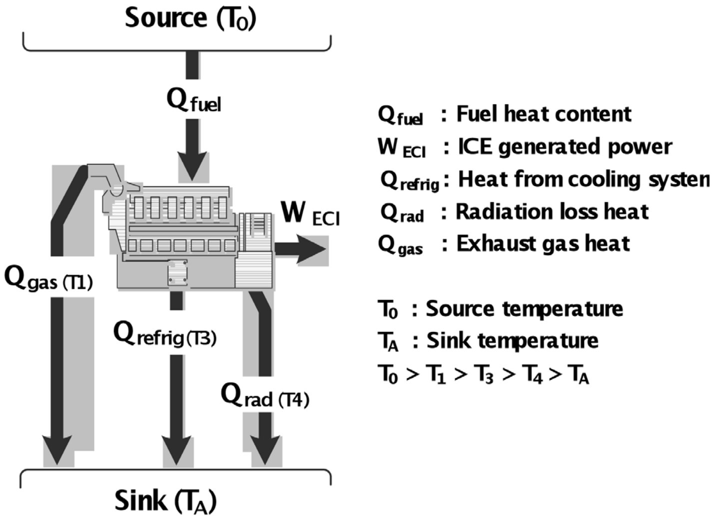

Figure 1. ICE Energy Balance

In this case, the cooling system temperature has two levels: The high temperature circuit operating between 85-93°C (from the engine into the radiator) and the low temperature circuit operating at 45-55°C (from the radiator into the engine) [8].

When there is a thermal energy demand (for heating or cooling), heat recovery systems can be used to in the form of cogeneration or trigeneration systems. Such recovery systems are designed with energy integration methods which can achieve overall system efficiencies in excess of 90% LHV [9].

In sites with no thermal energy demand, the fuel energy (heat) not converted into power by the ICE-generator, can be either rejected to the environment (wasted) or can be recovered through a sequence of strategically placed and sized heat exchangers (jacket coolant, lube oil and exhaust heat) to drive an ORC without affecting the ICE performance. This scheme allows one to recover in the form of high quality energy (electricity) as much as 80% of the heat otherwise wasted.

ORGANIC RANKINE CYCLE (ORC)

Organic Rankine Cycles, based on a reverse compression refrigeration or heat-pump technology, has been successfully applied for distributed generation. An ORC plant uses lower temperature heat sources, such as solar heat collected through various means, geothermal or any other significant source of waste heat—at temperatures roughly above the boiling point of water at sea level (> 100°C). However, with the exception of a few industrial processes, the technology has not been widely applied in industrial facilities.

The thermal processes occurring in an ORC power plant are similar to those in a conventional Rankine-cycle power plant with an evaporator (boiler or steam generator), expander (steam turbine), condenser, feed-water pump and sometimes a regenerator or economizer (Figure 2). In an ORC plant, instead of water, the boiler or evaporator is fed with an organic fluid such as (Isopentane, n-pentane, Ciclohexane, n-Butane, n-Octane, Isobutane, Toluene, etc.). See Figures 2 & 3 [10, 11, 12]. Such organic fluids have low evaporation enthalpy, lower than that of water, for a given temperature. By extension, at a given evaporation pressure, some organic fluids "boil" or evaporate at lower temperatures than water. Thus, these fluids are suitable to recovery low-temperature heat streams. However, for the same amount of heat transfer or duty (kWq)

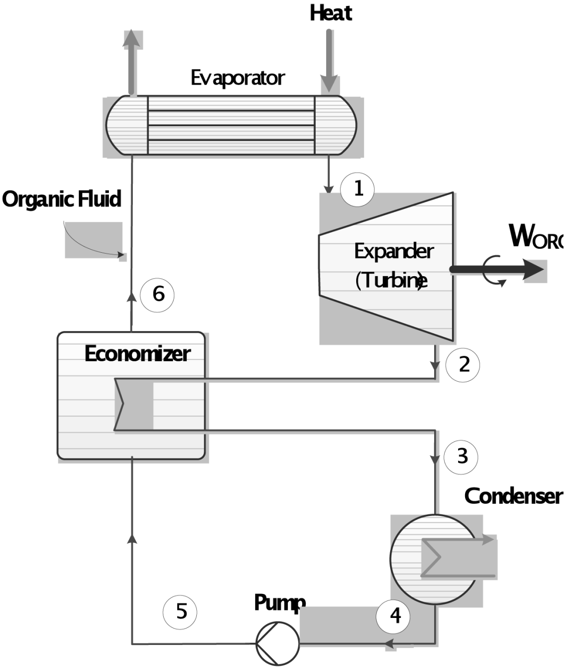

Figure 2. Schematic of an Organic Rankine Cycle with a Regenerator.

ORC plants have a higher installed cost than conventional steam plants. Nevertheless, ORC plants have two key advantages: (1) they use low temperature heat sources (as low as 50ºC above ambient temperature), and (2) the flexibility of matching the source and sink temperatures by specifying the most suitable of the available fluids—which span a wide range of thermodynamic properties. Thus, it's critical during system design to specify the optimal fluid for the source and sink temperatures, and their expected variation during system operation. Note source and sink temperatures, e.g. solar pond and desert ambient, respectively, can vary widely during the day and the year.

Most ORC plants operate at relatively low evaporation temperatures (70-300°C). Refer to Figure 3. Consequently, the evaporator can be heated by using a primary source of heating (say exhaust gas) or also through a secondary circuit recirculating a thermal oil which brings heat from a primary source to the evaporator, see Figure 3 [13, 14].

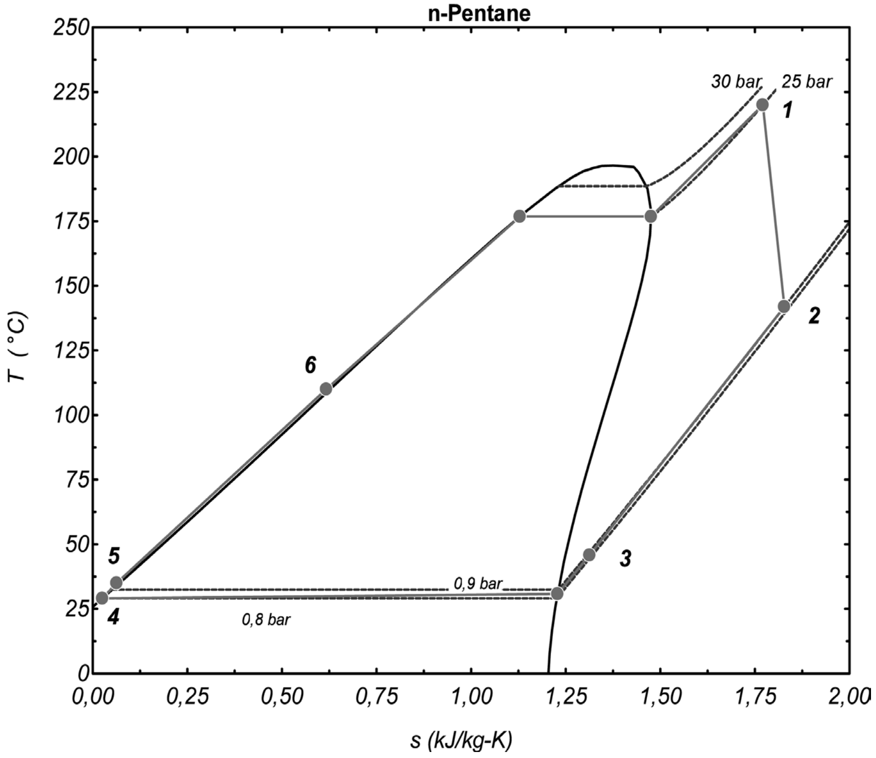

Figure 3. Entropy versus Temperature ORC diagram for n-Pentane

Let's consider the exhaust gas, which is the highest temperature available from all waste heat streams in an ICE. In the evaporator, the exhaust gas temperature reduces from T1 to T2, while the transferred heat evaporates the working fluid (Refer to Figures 3 and 4).

Next, the ORC electric efficiency (η_{ORC}) is computed as:

$$\eta_{ORC} = \frac{(W_{ORC} - W_{AUX})}{Q_{g(T1\rightarrow T2)}} \tag{2}$$

Where:

W_{ORC}: Electrical power generated by an ORC expander or turbine (kW).

$Q_{g(T1\rightarrow T2)}$: Heat recovered from the exhaust gas, which is cooled from T_1 to T_2 (kW).

W_{AUX}: Plant ancillary equipment energy consumption, including pumping, (kW)

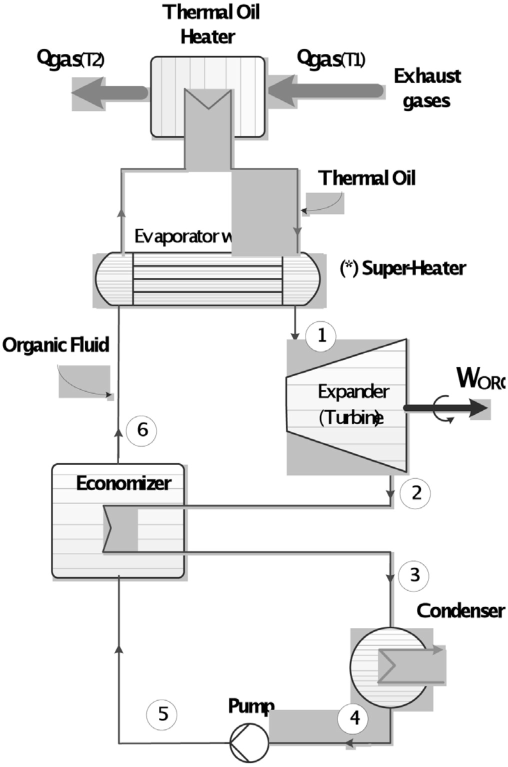

Figure 4. ORC heated with ICE exhaust gases

In practice, one can assume that: (i) in biogas ICE facilities,$T_{2(\text{MÍN})}$ ≈180°C; and (ii) the ancillary equipment consumption is roughly 5% of the turbine power output [15]. Therefore, Equation [2] can be expressed as

$$\eta_{ORC} = \frac{0{,}95 \cdot \dot{m}_{ORC}\left(h_1 - h_2\right)}{\dot{m}_g \cdot c_{pg}\left(T_1 - T_2\right)} \tag{3}$$

Where:

$\dot{m}_{ORC}$: mass flow rate of the working fluid (kg/s).

h_1 y h_2: turbine (vapor) input and output enthalpies (kJ/kg·K).

m_g: mass flow rate of the exhaust gas (kg/s).

c_{pg}: specific heat of the exhaust gas (kJ/kg·K).

T_1, T_2: exhaust gas temperature entering and leaving the evaporator (°C).

ORC plants are supplied and installed in modules—which include: evaporator, turbine, condenser, pump system and economizer or regenerator. The units are specified and supplied based on the available temperature levels and exhaust gas flow rate. Standard ORC modules vary in output capacity from 60 kWe through 2.7 MWe and higher, with power generation efficiencies ranging between 15-20% [16].

ICE+ORC COMBINED CYCLE PLANTS

Integrating ICE and ORC technologies we get a combined cycle plant, as schematically depicted in Figure 5. The electrical power efficiency for such a combined cycle (η_{CC}) is computed as:

$$\eta_{OC} = \frac{W_{ICE} + (W_{ORC} - W_{pump})}{Q_{fuel}} \tag{4}$$

Discounting the 5% pumping power, we obtain the equivalent form:

$$\eta_{OC} = \frac{W_{ICE} + 0{,}95 \cdot W_{ORC}}{Q_{fuel}} \tag{5}$$

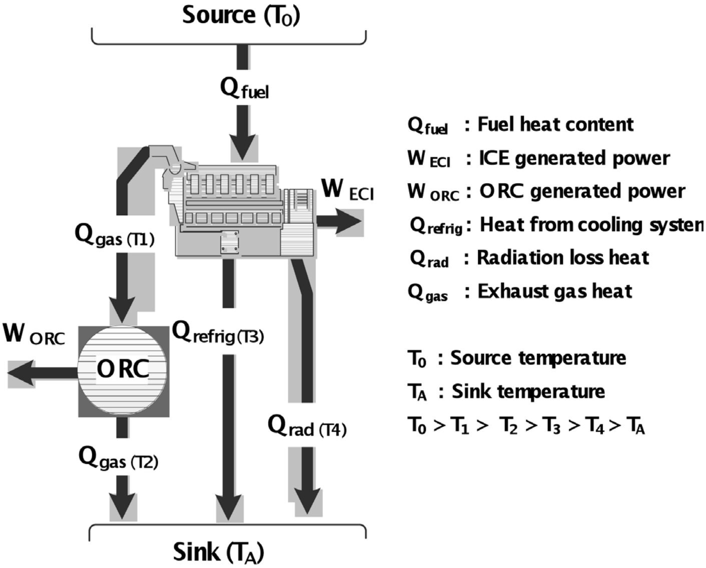

Figure 5. ICE + ORC combined cycle energy balance.

ECONOMIC EVALUATION OF ORC PLANTS

The installed cost per unit of output power for an ORC plant (in US\$/kW_{INS}) is usually higher than that of conventional technologies such as simple-cycle plants based on ICEs or gas turbines. However, when considering that an ORC plant recovers essentially “free” energy, from an otherwise wasted, relatively low-to-moderate quality and temperature heat stream, and convert the recovered energy into electricity for on-site use or for sale, it’s possible under some conditions to economically justify the investment in an ORC plant. We consider this is often the case with biogas-fired ICE distributed generation plants.

The total investment (Inv_{ORC}, US\$) in a number N_{ORC} of ORC modules computed as:

$$Inv_{ORC} = f_{INS} \cdot (k_{ORC} \cdot N_{ORC}) \tag{6}$$

Where:

f_{INS}: Installation cost factor (per unit).
k_{ORC}: Unit price per module (en US\$).
N_{ORC}: Number of ORC modules.

Next, the cost per unit of generated electrical energy (US$/kWh) is estimated by:

$$P_{eg} = \frac{f_{RC} \cdot Inv_{ORC}}{E_{ANUAL}} + C_{O\&M} \tag{7}$$

Where: $f_{RC} = \dfrac{i \cdot (1 + i)^N}{(1 + i)^N - 1}$ is the capital recovery factor (8)

The Electricity generated and sold/used in a year (kWh/year) is:

$$E_{ANUAL} = f_{D\_MACI} \cdot f_{D\_ORC} \cdot P_{ORC} \cdot 8.760 \tag{9}$$

i: Interest rate (% per year)
N: Planning horizon or plant economic life (years)
$C_{O\&M}$: Operation & Maintenance cost (US$/kWh)
f_{D_MACI}: ICE availability
f_{D_ORC}: ORC availability
P_{ORC}: Total installed ORC power output (kW).

The annual benefits or profit before taxes (US$/año) from selling electricity at a market rate p_{EM} (US$/kWh) is estimated by:

$$\text{Benefits} = (p_{EM} - p_{EG}) \cdot E_{ANUAL} \tag{10}$$

The simple payback period (years) is obtained by:

$$\text{Payback} = Inv_{ORC}/\text{Benefits} \tag{11}$$

CASE STUDY: ORC REPOWERING OF AN ICE POWER PLANT

The Bioenergía de Nuevo León power plant located in Monterrey, Nuevo León, México, started commercial operation in 2003. The plant houses 16 ICE modules, 1.059 kWe each, for a total installed output of 16.94 MWe. The engines are fueled with landfill biogas. The objective of this study is to evaluate the retrofit of an existing ICE power plant with ORC. Figure 6 depicts the evaluated combined cycle plant. Table 1 lists the operating data for the biogas ICE modules.

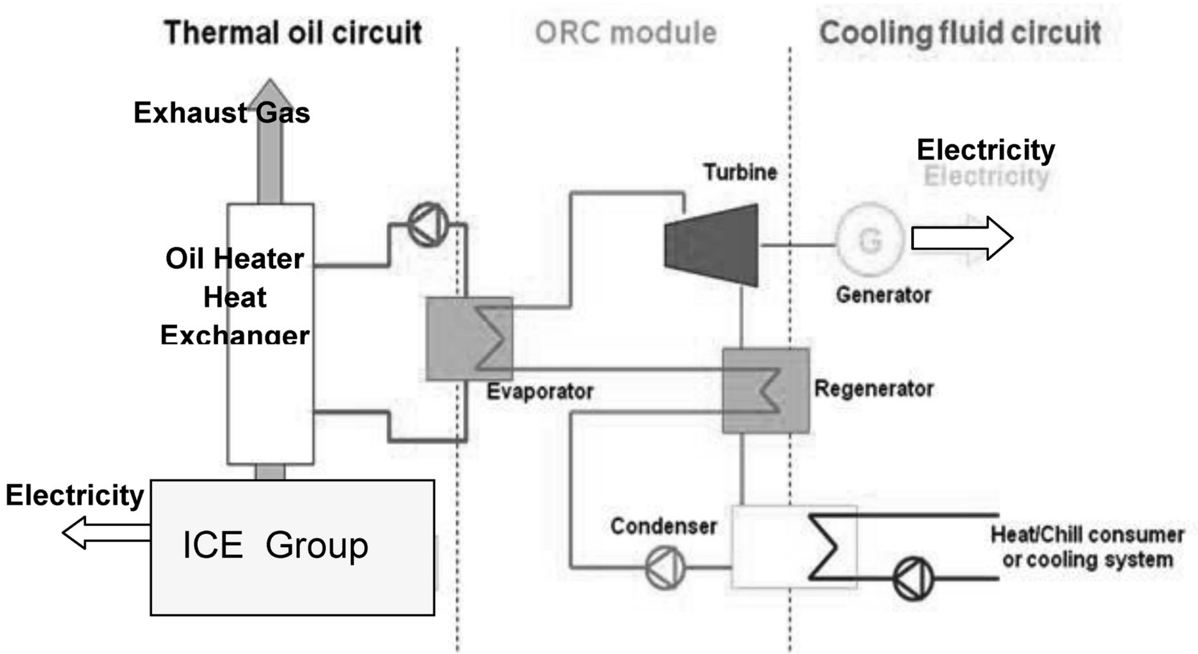

Figure 6. Combined cycle plant with ICE thermal oil circuit, ORC module and cooling circuit.

Table 1. Operating Data of ICE and Oil Heating Heat Exchanger Bioenergía de Nuevo León S. A. CV Power Plant

Biogas fired ICE Module: All data at rated output
Unit rated power output: 1.059 kWe
Biogas consumption: 2.715 kW (pci)
Electrical efficiency: 39 % (LHV)
Exhaust gas flow rate: 5.645 kg/h
Exhaust gas temperature: 490 °C

Thermal oil heat exchanger effectiveness: 91 %
Duty of exhaust gas-to-oil heat exchanger (*) : 487 kW

(*) Exhaust gas cooled to 180 °C (leaving HX temperature)

The 16 ICEs reject 7,792 kWt of waste heat to the environment. Next, to recover such heat, the ORC plant configuration must be specified. Specifically, to achieve the most economical and reliable operation, we need to determine the number of ORC modules to be installed. The following alternatives have been considered:

A) Install 16 ORC modules, each one to be connected with one of sixteen (16) ICEs.
B) Install 8 ORC modules, each one to use the heat from two (2) ICEs.
C) Install 4 ORC modules, each one to use the heat from four (4) ICEs.
D) Install 2 ORC modules, each one to use the heat from eight (8) ICEs.
E) Install 1 ORC module to be connected to the sixteen (16) ICEs.

Economic Evaluation

To evaluate the five alternatives listed above, we use all the previously defined equations [1 through 11] and assume the following values:

$f_{INS} = 1.40$
$i = 12\%$
$N = 20$ years
$C_{O\&M} = 0.012$ US\$/kWh
$f_{D\_MACI} = 0.95$
$f_{D\_ORC} = 0.90$
$f_{CO2} = 370$ g/kWh [16].

Table 2 summarizes the technical and economic evaluation information for alternatives A, B, C, D and E.

Table 2. Technical and Economic Evaluation Information for ORC Retrofit

Item	**(#)**	**A**	**B**	**C**	**D**	**E**
Number of ORC modules	(1)	16	8	4	2	1
Number of ICE's for each ORC module	(2)	1	2	4	8	16
Available ICE heat to each module, kWt	(3)	487	974	1,948	3,896	7,792
ORC module commercial size, kWe	(4)	60	165	300	750	1,500
Total installed capacity, kWe	(5)	960	1,320	1,200	1,500	1,500
Cost of each ORC module, 10^3US$	(6)	550	900	1,200	1,850	2,500
Annual electricity production, GWh/yr	(7)	7.19	9.89	8.98	11.24	11.24
Power generation unit cost, US$/kWh	(8)	0.229	0.1485	0.1121	0.0737	0.0537
Heat recovered by module, kWt	(9)	455	916	1505	3595	7190
Fuel use efficiency	(10)	0.132	0.18	0.199	0.209	0.209
Combined cycle efficiency	(11)	0.412	0.42	0.417	0.425	0.425
Efficiency improvement	(12)	0.022	0.03	0.027	0.035	0.035
Avoided CO_2 emissions, 10^6 Tons CO_2/yr	(13)	2,660	3,659	3,323	4,159	4,159
ORC plant installed unit cost, 10^3 US$ / kWe	(14)	9.1667	5.4545	4.0000	2.4667	1.6667

CONCLUSIONS

The ORC modules are supplied in standard sizes, thus in practice, it's not possible to utilize all the available ICE waste heat. See rows (3) vs. (9) in Table 2. In other words,

$$\text{Heat recovered by each ORC module} \leq \text{Available ICE heat to each module (kWt).} \qquad (12)$$

Although ORC module cost is high (US$/kW$_{INS}$), economies of scale favor investment in larger plants, thus reflecting lower unit cost of larger modules. As seen in Table 2, larger module installation results in lower electricity rates [$p_{EG(E)} < p_{EG(D)} < p_{EG(C)} < p_{EG(B)} < p_{EG(A)}$], better profits and quicker paybacks (Figure 7). Note in Table 2, the larger the module size (item 4, kWe), the lower the overall ORC plant installed unit cost (item 14, in 10^3US/kWe).

Figure 7 depicts the influence of the market Price of electricity over the payback or capital recovery period for the five considered repowering alternatives:

> Option **A** is not economically viable (a small part of the curve is in the upper right hand corner). All paybacks are greater than 24 years for the foreseeable market prices.
>
> Option **B** can be economically viable (payback < 8 years) when the electricity prices are higher than 0.27 US$/kWh.
>
> Option **C** can be economically viable (payback < 8 years) when the electricity prices are higher than 0.20 US$/kWh.
>
> Option **D** can be economically viable (payback < 8 years) when the electricity prices are higher than 0.18 US$/kWh.
>
> Option **E** can be economically viable (payback < 8 years) when the electricity prices are higher than 0.09 US$/kWh.

The best repowering alternative is to install one 1.5 MWe ORC module in conjunction with all the existing 16 ICEs (option **E**). This would increase the current ICE capacity of 16.94 MWe to a total pro-

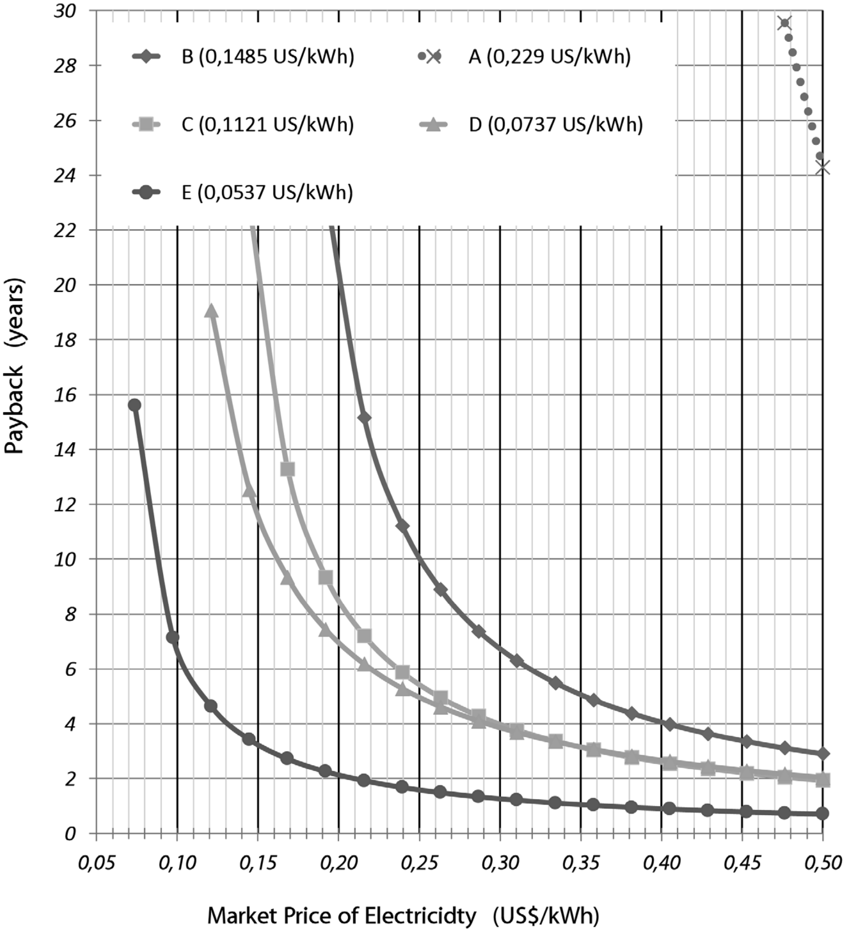

Figure 7. Electricity Prices (X axis) versus Payback Periods (Y axis) for the five alternatives (A, B, C, D, E). Each alternative defines a distinct electricity production cost (US $/kWh).

duction of 18.44 MWe. This is equivalent to augmenting the current installed capacity by 8.9%. This option would generate 11.24 GWh/ year of electricity. Since the ORC system operates with heat otherwise rejected to the environment, the new plant would avoid emitting to the environment 4,159 M.T. of CO_2 per year.

Generally, in the majority of industrial thermal processes, it is possible to identify low temperature waste heat. In these cases, the use of *Thermal Integration Concept* is suitable to design a maximum heat recovery system for ORC cycles to produce electricity and heat (cogeneration). So, we would be able to: (1) diminish the energy costs of manufactured products; (2) sell the electricity surplus; and (3) improve the business competitiveness.

For Further Research and Development

This article has presented a conceptual design methodology for a combined cycle which integrates ICE and ORC technologies. To continue with a more detailed design and analysis, the next methodology will involve the engineering modeling and economic optimization of the thermal fluid handling and heat exchanger network with respect to the plant layout and number of ORC modules. For the case study herein, each one of the possible alternatives (A through E) listed on Table 2 implies a different fluid handling system design and layout. In addition, each alternative implies a different operating strategy and its corresponding reliability, availability and maintainability (RAM). The two extreme cases (Alternatives A and E) of such fluid handling system are described next in terms of their RAM impact.

> (A) One smaller ORC module dedicated to one ICE would be the simplest fluid handling system, from a piping and pumping complexity view point. However, if one or some of the ICE or ORC modules are down, due to a forced or scheduled outage, the rest of the system may continue to operate and generate heat and power. Any module can be maintained with minimal impact to the operational readiness to the whole system.
>
> (E) On the other extreme, a single large ORC module interconnected with all the ICE units through a piping and heat exchanger network would be the most complex fluid handling and pumping system. In this case, if one or some of the ICEs goes down, the rest of the ICEs can generate power and the ORC module may generate power at partial capacity. But if the ORC module goes down, due to forced or schedule maintenance, the whole heat recovery scheme will be paralyzed during the outage.

From the above discussion, we realize that reliability, availability and maintainability are critical design and operation characteristics in an energy conversion system. Thus, a future development will involve understanding and evaluating the impact of plant-layout complexity and system redundancy in the RAM and life-cycle cost of an ICE+ORC combined cycle plant.

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