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INTEGRATED SOLAR COMBINED CYCLE POWER PLANT USING ORGANIC RANKINE CYCLE FOR RELIABLE, DISPATCHABLE, LOW CARBON ELECTRICITY

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ABSTRACT

Renewable energy has a significant role to play in helping the world to achieve the greenhouse gas emission reduction necessary to achieve the pathway to a 2°C increase in global temperature. Electricity generation from wind and solar resources can contribute immensely to the de-carbonization of power generation, but these resources are intermittent. High penetration of intermittent renewable power generation can cause grid stability and control issues for network operators, with fast response fossil fuel power plant necessary to provide security of supply and maintain grid stability. Increasingly natural gas-fueled distributed power generation is being installed to provide the necessary grid support.

However, hybrid power plants comprised of a fossil fuel power generating system, a renewable power generation system and energy storage can provide both the low CO_2 electricity required to meet environmental constraints, and the dispatchability and stability required by grid operators. Integrated Solar Combined Cycle Power Plants (ISCCs), comprising a Concentrated Solar Power plant and a natural gas fired combined cycle plant, have the potential to simultaneously reduce fossil fuel consumption, provide secure, highly predictable electricity generation, and reduce the cost of integrating renewable energy into a power system.

While a number of ISCCs have been built at a larger scale (above 150 MW power output), the concept has rarely been adopted for smaller scale distributed power applications. In addition, the traditional ISCC concept uses a steam bottoming cycle, which consumes water, and often locations where distributed ISCC could be utilized suffer from a scarcity of fresh water.

This paper evaluates whether replacing the steam bottoming cycle with an Organic Rankine Cycle (ORC) alternative can provide a simpler, lower cost distributed ISCC solution that can be utilized on smaller and island grid systems, or mini- and micro-grids, to provide an affordable, water-free, low carbon power generation system.

1. INTRODUCTION

The past 10 years have seen a significant change in the power industry. The drive to decarbonize electricity generation has resulted in a significant increase in the installed capacity of renewable power generation, in particular wind and solar. These intermittent sources of power generation are creating challenges for grid operators, and causing the existing installed fossil fuel generation base to operate in a significantly different manner.

The intermittency of wind and solar power requires fossil fuel back-up power generation to be available to support the grid demand, and to respond rapidly due to fluctuations in renewable power output. Natural gas is seen as the bridging fuel between today's power system and a future zero carbon system as it is the cleanest, lowest carbon fossil fuel available, while the gas turbines and gas engines designed to operate on this fuel can provide the flexible power needed to support a grid system with a significant percentage of intermittent renewable power generation.

Another change being seen in the power industry is the increased deployment of distributed power plants – placing the power generation close to the actual load centers. This provides towns and cities, or more remote areas, with improved security of supply as they are no longer wholly reliant on transmission systems to supply power from remotely located centralized power plants. It also reduces the investment costs as the power plants tend to be smaller, while reducing the need to make investments in the electricity transmission system. Distributed power plants also avoid the power losses in the transmission system, while providing the grid operator with a power plant that can provide inertia, voltage support and frequency support to help keep the grid system operating within its required voltage and frequency limits.

In a number of countries, the subsidies paid for renewable power have led to a boom in construction of utility scale wind and solar 'farms'. While the rapid deployment of such large capacities of these technologies has led to a fall in their costs, the need to provide back-up power for when the sun isn't shining and the wind isn't blowing has often been overlooked, leading to the need for Capacity Mechanisms to encourage the construction of, or to maintain in operation, the fossil-fueled power plants required to ensure security of supplies.

Electricity is a key commodity for today's world, and is seen as being necessary for both economic growth and to improve health and quality of life. Globally there are still more than two billion people without any access to electricity or a reliable electricity supply, providing a huge challenge in how to provide secure, affordable electricity without compromising the political commitments made to reducing human impact on the global environment. In many places in the developing world, the large-scale renewable power plants are not really viable: the necessary power transmission capacity is lacking, the overall power demand is not high enough to justify such a large plant, the low capacity factors of intermittent renewables do not solve the problems of lack of installed power generation capacity to provide security of supplies, and the land area required simply is not available. Add to this the cost of building fossil-fuel power stations to support these intermittent renewables, and the cost of electricity – already high in many of these places compared to developed nations - becomes unaffordable for many, without the intervention of Government to subsidize prices, which they can often ill-afford to do.

Co-locating renewable generation with a fossil fuel distributed power plant can help achieve these aims: by sharing infrastructure and the skilled manpower required to operate a facility, overall costs are reduced: by integrating the renewable power generation with the fossil fuel power plant (and energy storage), fossil fuel consumption can be displaced with a positive economic and environmental benefit.

While wind and solar PV have been grabbing the majority of the renewable power headlines in recent years, great advances in cost reduction have been made in Concentrated Solar Power (CSP), also known as Solar Thermal Electricity (STE) technologies. Recent projects have been awarded with power prices below US$100/MWh for CSP facilities based on the steam or water rankine cycle. Combined cycle gas turbine (CCGT) power plants are among the most efficient forms of power generation, and if CSP technologies are combined with CCGT configurations, then secure, dispatchable power can be generated efficiently, economically and with a reduced environmental footprint. As quoted by Susan Kraemer in an article for Solar Power and Chemical Energy Systems [(1)], 'The Solar Century will change the electric grid'. Combining CCGT and CSP can provide a single source of electricity generation that can provide both baseload low carbon electricity and that can act as 'gap filler' for a system with lots of intermittent renewable generation

NOMENCLATURE

CCGT	Combined Cycle Gas Turbine
CO_2	Carbon Dioxide
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiation
HTF	Heat Transfer Fluid
ISCC	Integrated Solar Combined Cycle
ISORCC	Integrated Solar Organic Rankine Combined Cycle
LCOE	Levelized Cost of Electricity
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
ORC	Organic Rankine Cycle
PV	Photovoltaics
STE	Solar Thermal Electricity
WHRU	Waste Heat Recovery Unit

2. INTEGRATED SOLAR COMBINED CYCLE (ISCC)

The global technical potential of concentrating solar power amounts to almost 3,000,000 TWh/y, a number considerably larger than the present world electricity consumption. This renewable energy resource is mainly concentrated in the desert regions where under the correct conditions, CSP plants with large solar fields and thermal energy storage are in theory capable of producing base load electricity at full capacity for up to 8000 hours per year, although currently this may not be economically feasible. While the costs of such systems are still high today, they can become a competitive option for electricity supply in the future. The distribution of potential areas for CSP worldwide has been mapped and confirms the possibility for solar electricity to be applicable to many regions of the world.[2]

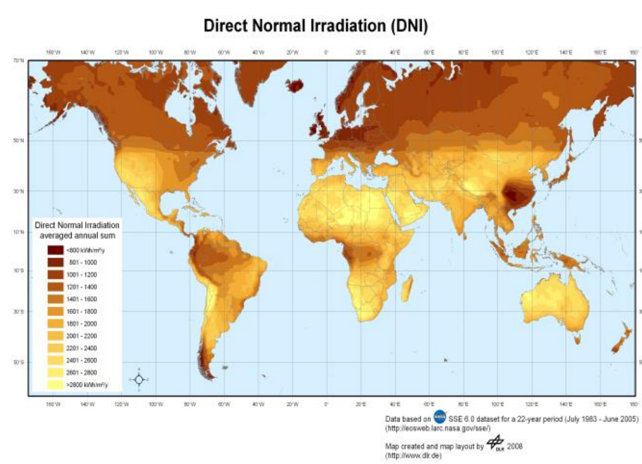

Figure 1: Global Solar Resources (see reference 2)

Whether there is sufficient space in populated regions to permit baseload operation of CSP is unlikely, so security of supply will rely on transmission of the solar generated over potentially large distances. This means solar power, just like fossil fuel power, will be vulnerable to transmission system disruption through adverse weather conditions or system stability. A hybrid system requiring less space could provide a distributed power solution suitable for more densely populated regions, countries or regions with limited suitable locations for solar fields, or island states with limited available land mass.

3. SOLAR PV OR SOLAR THERMAL?

While both harness their energy from the sun, CSP and PV are in many respects diverse technologies with very different uses. PV has come to dominate all smaller-scale solar electricity applications, while retaining the majority market share even in commercial and utility-scale applications. CSP retains a strong niche at the utility-scale and in combined heat and power applications, where no amount of PV cost reduction is expected to overcome its inherent technology advantages[3].

While CSP requires slightly less direct area on a m^2/GWh/year basis than solar PV (2.7 compared to 3.1) according to NREL[4], this is technology dependent. The key advantage of solar thermal is the incorporation of high efficiency, low cost, low degradation energy storage. Solar thermal technologies have an inherent advantage in that the energy produced can be easily stored as heat with high efficiencies, whereas PV requires the produced electricity storage in batteries. The Energymag blog advises round trip efficiencies for batteries of 75 to 90%, whereas thermal storage system manufacturers, such as Energynest, quote a 24 hour round trip efficiency as high as 99% for thermal oil storage systems, although the actual AC to AC ‘round trip’ efficiency of thermal storage will depend on the efficiency of the power plant, which will cause batteries to have the better round-trip performance. The cost of thermal storage is also very competitive compared to batteries – Energynest advise a typical installed cost for a thermal oil storage system today of US$25/MWth (equivalent to US$125/MWh electrical if a 20% heat to electricity conversion efficiency is considered), whereas battery costs are currently around US$450 – 550/MWe and unlikely to fall to a US$125/MWh value for many years to come. Degradation of thermal storage technologies is also very low, whereas batteries will degrade both with age and due to cycling.

While energy storage is not essential, it assists a distributed power plant to follow load demand when operating in isolation from a grid system, or to help meet peak demands on a larger system. While peak solar power generation occurs in the middle of the day, in many places the peak electricity demand occurs in the evening, as shown in Figure 2.

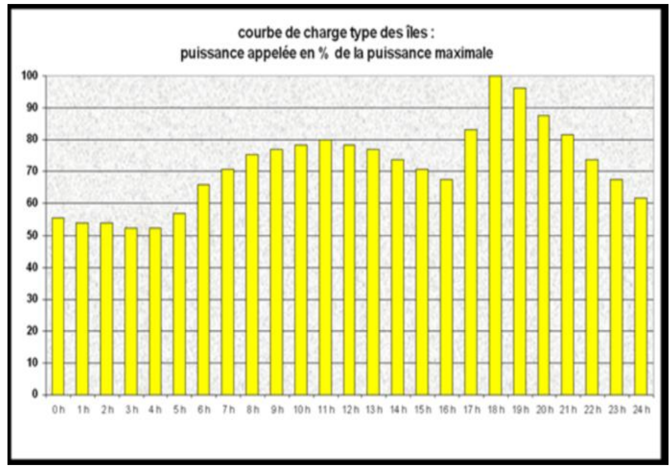

Figure 2: Typical island nation load profile (courtesy EdF)

While solar PV and batteries work extremely well as a standalone small-scale, short-term solution, it is more difficult to integrate with a fossil fuel power plant as there is little shared infrastructure. CSP and thermal storage on the other hand can be integrated into the bottoming cycle of a gas turbine-based power plant, eliminating the need for separate electrical switchgear systems by using the turbine installed in the bottoming cycle to generate the solar power.

4. INTEGRATED SOLAR COMBINED CYCLE (ISCC)

An ISCC power plant combines a CSP facility with a natural gas-fired gas turbine combined cycle (CCGT) power plant. The heat produced by the CSP is used to generate additional steam that is integrated into the bottoming cycle of the gas turbine. ISCC plants effectively help integrate intermittent solar power into the grid by circumventing the non-dispatchability of the CSP while providing reductions of operating costs and capital costs, and offering the possibility of increased operational flexibility compared to a stand-alone CCGT [5]. An ISCC plant is capable of operating as a base-load plant but with increased fossil fuel efficiency, and therefore reduced CO_2 emissions, compared to a conventional CCGT

The basic concept of an ISCC is shown in Figure 3. The combined cycle plant operates as normal, but with an over-sized steam turbine to take into account the steam generated by the solar field.

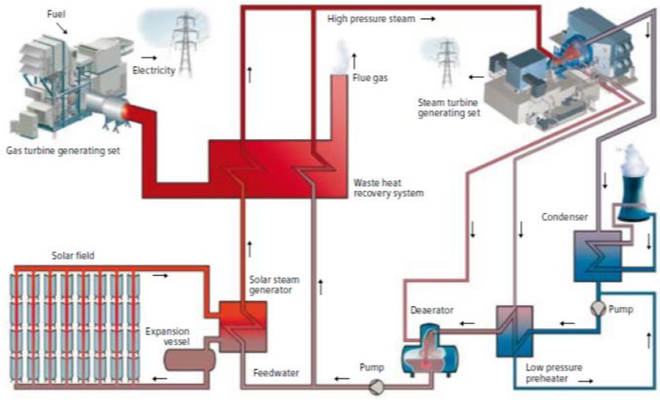

Figure 3: Typical Integrated Solar Combined Cycle (ISCC) schematic

The solar field heats a Heat Transfer Fluid (HTF), which then produces steam in the solar steam generator. This steam is then superheated in the waste heat recovery unit (WHRU) behind the gas turbine to provide steam for the steam turbine at the correct temperature. The HTF is usually thermal oil, but molten salts can also be applied for higher temperature solutions. The total potential power output is higher than that achievable from a CCGT alone, thus reducing the fossil fuel consumed per MWh generated.

An ISCC can of course operate as a load-following plant either meeting the required demands of the grid operator, or in the so-called island mode operation, where it is not connected to a grid system, by varying the load on the gas turbine and allowing the solar field to contribute as much energy as possible. Messrs Franchini, Perdichizzi and Ravelli of the University of Bergamo have modelled such situations in a paper presented at PowerGen Africa in 2016[6]. As shown in Figure 4, the ISCC efficiency during daylight hours exceeds the efficiency achievable from a CCGT alone. The predicted efficiency increase is dependent on the season and solar field technology, but all options show a significant efficiency boost which leads to an increased daily average operating efficiency.

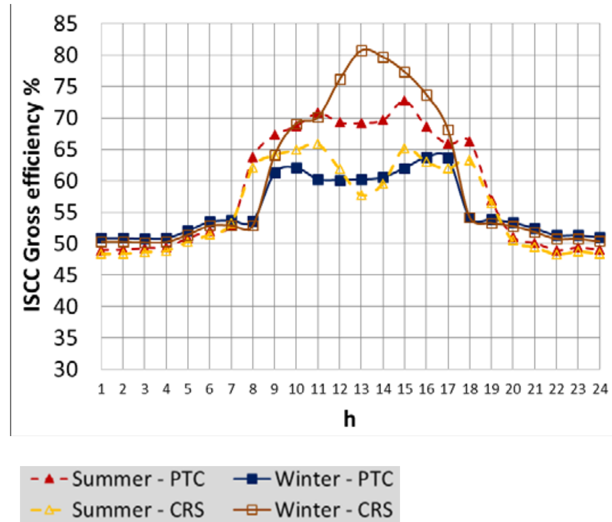

Figure 4: ISCC Gross Efficiency prediction for an industrial load (see reference 6)

ISCC to date has mainly been employed at a large scale (>150 MW) to take advantage of economies of scale. News articles indicate that the latest ISCC plants – Duba 1 and Waad Al Shamal in Saudi Arabia – will have very competitive installed costs: the 605 MW Duba 1 plant, incorporating a 43 MW parabolic trough system will have a quoted installed cost of US$1,096/kW while the 1,390 MW Waad Al Shamal will have a 50 MW CSP and a quoted installed cost of US$705/kW. However, it should be noted that the solar component, the more expensive part of the installation, is small compared to the total plant output.

The LCOE from an ISCC plant is also quite competitive compared to that of CSP alone. Alqahtani and Patino-Echeverri[5] report an LCOE from ISCC to be 35 – 40% less than that of a stand-alone CSP, with an example for a US-located plant with a 50 MW CSP field calculated as 11.3c/kWh for the ISCC compared to 19.1c/kWh for the stand-alone CSP.

IRENA data in their 2012 report[7] indicates an LCOE for CSP between 16c/kWh and 36c/kWh depending on the solar field technology, whether wet or dry cooling is employed and whether storage is installed, although the average appears to be around 26c/kWh. This suggests that ISCC should be targeting LCOEs in the region of 10c/kWh to 16c/kWh.

Distributed power plants although smaller in scale, cannot take advantage of these economies of scale and so the installed costs will be higher on a US$/kW basis. There are three potential drawbacks to ISCC for distributed power applications that are apparent: the complexity (and hence additional cost) of producing the steam at the conditions required by the steam turbine, the inability to generate from the solar field if the gas turbine is not operational, and the need for water. Water scarcity is an increasing issue in many parts of the world, and power generation competes with the domestic, agricultural and industrial sectors for this valuable resource.

5. GAS TURBINES AND ORGANIC RANKINE CYCLE (ORC)

Organic Rankine Cycle technology is not new, but has rarely been applied in combination with gas turbines to generate electricity from the energy remaining in the exhaust gases. Most gas turbine plus ORC references are retrofits on to gas turbines installed at gas compression stations, although there are some more recent references in gas turbine power generation applications in Uzbekistan for units installed on oilfields. However, the principle is very suitable for the types of gas turbine used in distributed power applications, especially where water is not available or is an expensive commodity.

5.1 Gas Turbine Combined Cycle using ORC technology

While gas turbines used in large centralized power plant are optimized for combined cycle operation with high exhaust gas temperatures for maximizing the steam cycle efficiency, this is not necessarily the case for the smaller gas turbines applicable to distributed power plants. The high efficiency light industrial and aero-derivative gas turbine models used in these applications tend to have exhaust gas temperatures in the 425°C to 550°C range, and while they can be used in 'steam' combined cycle applications, the highest efficiencies can only be achieved at a relatively high cost. This temperature range though is ideal for ORC technologies, which although they will not achieve the same potential efficiencies as a traditional 'steam' combined cycle, are predicted to offer considerable cost savings, leading to a very similar Levelized Cost of Electricity (LCOE).

There are three basic forms of ORC cycle that can be employed with gas turbines: the indirectly heated concept where a heat transfer fluid (HTF), normally thermal oil, is used to recover heat from the exhaust as stream and to vaporize the working fluid that drives the ORC turbo-generator; the directly heated concept where the ORC working fluid is vaporized directly by the gas turbine exhaust heat; and the Cascade Concept, which is similar to the indirectly heated configuration, but differs in that the HTF is vaporized and the heat of condensation of the HTF used to vaporize the working fluid in the ORC turbo-generator loop.

Most current ORC installations with gas turbines are based on the indirectly heated concept. While the least efficient of the three options, for ISCC purposes it has the advantage that the same working fluid can be used in the WHRUs and in the solar field, simplifying the whole ISCC concept. It is also easier to integrate multiple heat sources into the indirectly heated solution. Various working fluids can be used to drive the ORC turbine, but for high temperature applications, such as heat recovery from gas turbines, cyclopentane currently appears to show the best overall performance and economic results according to ORC manufacturers' test results and calculations.

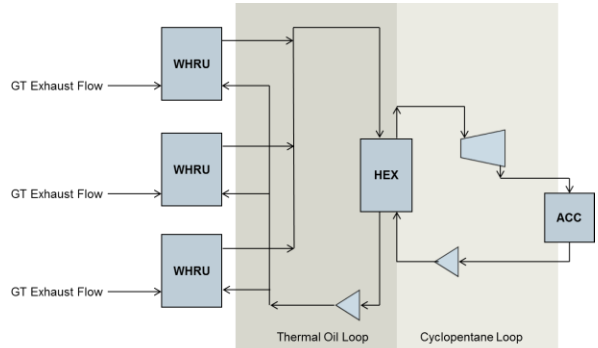

Figure 5: Simplified schematic of the indirectly heated ORC concept as applied to gas turbines

5.2 ORC in CSP applications

While steam turbines dominate current CSP applications, ORC plant have been constructed for CSP applications. One of the leading ORC OEMs, Turboden S.p.A., advise on their website four ORC references in CSP applications, although all are quite small. In all cases, the indirectly heated concept is employed.

One reference plant, a 0.6 MW unit, has been installed in Sardinia[10] under the ERDF 2007-2013 program to assess under real operating conditions the performance, effectiveness and reliability of small-scale CSP in distributed generation. A second reference plant is a 2 MW unit installed at a cement factory in Morocco, where the heat recovered from the cement kilns is supplemented by solar thermal input from parabolic troughs to boost power generation. There is also a biomass/CSP hybrid ORC installation in Denmark which commenced operation in 2018.

Figure 6: Hybrid CSP/Waste Heat Recovery Plant in Morocco (courtesy of Turboden S.p.A.)

6. INTEGRATED SOLAR ORGANIC RANKINE CYCLE (ISORCC)

ISORCC is a concept that combines the benefits of ISCC with the advantages of the ORC cycle to simplify the ISCC concept, reduce the costs, eliminate the need for water and make the ISCC concept more applicable to distributed power applications.

6.1 The ISORCC concept

Like ISCC, ISORCC employs the principle of the solar field providing additional heat to the bottoming cycle of a gas turbine. Unlike ISCC, ISORCC permits the same working fluid – typically a thermal oil with high thermal stability such as VP1 - to be used in the solar field and in the gas turbine WHRU. This simplifies the heat recovery systems, and reduces the cost as a thermal oil heater is less expensive than a steam generator as no phase change of the HTF takes place. Hot oil directly from the solar field is mixed with hot oil from the gas turbine WHRUs and is fed to the single evaporator on the ORC circuit – there is no need for a heat exchanger on the solar thermal system. The simplified concept schematic for ISORCC is shown in Figure 7.

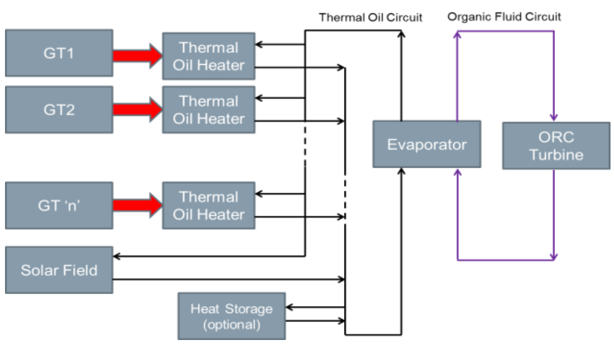

Figure 7: Simplified schematic for Integrated Solar Combined Cycle (ISORCC)

As well as being able to integrate multiple heat sources to feed a single ORC turbo-generator, this concept has the additional benefit in that the heat sources can operate independently of each other. Thus, while the concept is based on the solar field complementing the het input to the ORC from the gas turbines, it is possible that in periods of low load low demand, power requirements could be met using the solar field alone, or the gas turbines used as back-up power for a CSP installation.

6.2 The potential competitiveness of ISORCC

To evaluate whether ISORCC could offer a competitive solution for distributed power applications, a simple study was carried out for a base load natural gas-fueled power plant located at sea level with a nominal constant 35 MW power output with a constant ambient air temperature of 40°C. The plant was based on a Siemens SGT-750 gas turbine feeding an indirectly heated ORC system, with the gas turbine load decreasing as the solar thermal energy generation increases to maintain a constant power plant output. The solar field was assumed to be parabolic trough collectors using thermal oil as the HTF, with no energy storage considered.

Various solar field sizes have been calculated to provide up to a maximum of 50% of the required ORC heat input, to see the impact of solar field size on both capital costs and LCOE and determine whether there is an optimum size. In this arrangement, the ORC is over-sized compared to that required for a gas turbine only to ensure the nominal plant output of 35 MW can be achieved with the gas turbine operating at 50% load.

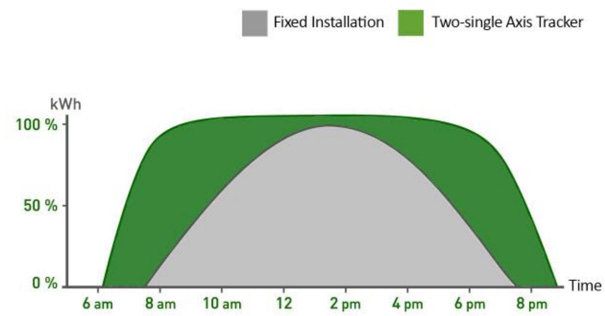

Figure 8: Typical solar daily irradiation variation.

For this paper, only the fixed installation solar characteristic shown in Figure 8 was considered. Maximum solar output was considered to equate to the gas turbine operating at 50% load, while zero solar output corresponds to 100% gas turbine load and 50% of maximum solar output to 75% gas turbine load. The system was evaluated for two different Direct Normal Irradiation (DNI) levels and for three different fuel costs. The results are summarized in the following sections, with detailed calculations contained in Appendix 1.
It should be noted that 40°C was selected as the ambient temperature to produce a 'worst case' scenario for gas turbine performance. In a real-life scenario, this ambient temperature occurs only in certain regions, and is unlikely to be constant over a 24 hour period even in these regions.

6.3 Predicted ISORCC Performance

The Siemens SGT-750 is a high efficiency light industrial gas turbine. At 40°C, sea level, the predicted power output is 28.29 MW at a gross efficiency of 36.7%, with an exhaust gas flow of 93.0kg/s and an exhaust temperature of 493°C. Under these conditions, an indirectly heated ORC system with an assumed gross efficiency of 20% will generate an additional 7.35 MW bringing the total power plant gross output to 35.82 MW with a gross efficiency to 46.5% on an LHV basis (compared to the 48.5% that could be expected for a conventional steam combined cycle for the same ambient conditions).

As the gas turbine load reduces, the efficiency, exhaust gas flow and exhaust temperature all reduce. With reduced exhaust gas flow and temperature, the heat input to the ORC system reduces, requiring the solar field to supply sufficient heat to compensate for the reduced energy input from the gas turbine to maintain a constant power plant output. The power plant gross fossil fuel efficiency with reducing gas turbine output and the calculated percentage heat input to from the solar field is given in Figure 9.

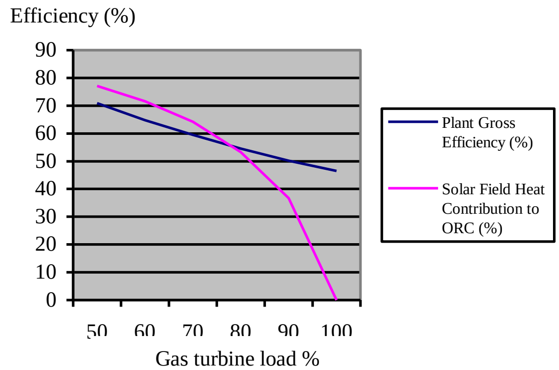

Figure 9: Predicted gross efficiency and solar field heat input to the ORC as a percentage for a 35 MW ISORCC power plant based on a Siemens SGT-750 at 40°C ambient temperature

Figure 9 shows that, as expected, the power plant efficiency increases as the solar thermal input to the ORC increases, achieving potentially levels well above that achievable by the gas turbine and ORC alone. However, the solar field contribution is not constant over a 24 hour period, so it was assumed that maximum solar field input would occur in the case where the gas turbine was operating at 50% load. Based on different operating hours at different gas turbine loads, it was calculated that the average daily power plant gross efficiency is expected to be 51.7%, still a significant increase over the non-solar contribution case (46.5%) and better than a conventional steam combined cycle case.

While larger solar fields increase the plant efficiency, they also increase the cost, so efficiency alone is not a satisfactory decision factor on the size of the solar field. Further analysis is required to determine the optimum minimum load for the gas turbine, which in turn determines the necessary solar field size.

6.4 Capital Costs

Because the baseline for the study is for an ambient temperature of 40°C, the installed cost for the gas turbine and ORC are inflated when considered on a US$/kW basis compared to the normal situation when the gas turbine output is considered at 15°C. However, it was decided to continue with the evaluation at 40°C to give confidence that the calculated installed costs could be achieved under other conditions, and could be compared with the reported costs for a stand-alone CSP installation.

The major contributor to the total installed cost is the solar field. To calculate the required area of the solar field for both a high DNI instance (2,700kWh/m^2) and the low DNI instance (2,100kWh/m^2), the solar collector efficiency must be considered. The paper written by Franchini et al[6] examines the relative solar to thermal efficiencies in summer and winter for both parabolic trough and solar towers. The daily summer efficiency for a location in southern Africa is shown in Figure 10, and while the solar tower system showed a small reduction in efficiency in winter, the reduction for the parabolic troughs was considerable.

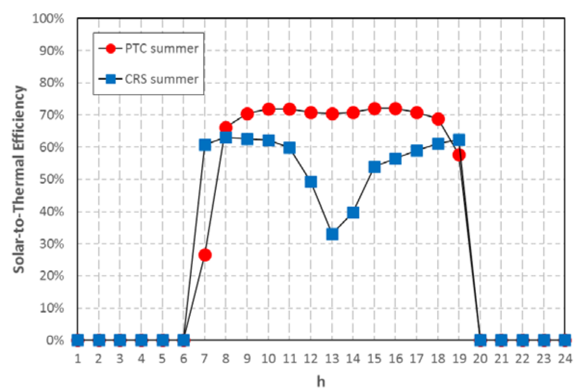

Figure 10: Solar to thermal efficiency for parabolic trough collectors (PTC) and solar tower (CRS) in summer for a southern Africa location (see reference 6)

For simplification, it was assumed that the site would be located nearer the equator and an average daily solar-to-thermal efficiency of 50% assumed for the parabolic troughs. Based on feedback for a recent European project, a cost for the solar field of US$255/$m^2$ was assumed. The installed cost of the complete ISORCC plant was estimated for the different gas turbine loads to analyze the impact of the increasing solar field size as gas turbine loads reduces, and the results on a US$/kW basis are shown in Figure 11.

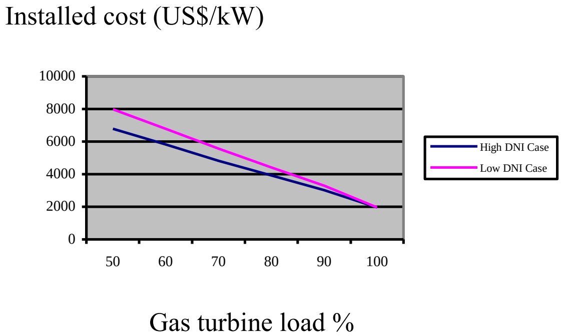

Figure 11: Estimated installed cost in US$/kW for a 35 MW ISORCC plant for varying gas turbine loads (calculated on a 40°C ambient temperature basis)

IRENA estimate in their CSP cost analysis report[7] that the 2011 installed cost for a CSP plant with no storage is US$4600/kW. Alqahtani and Patino-Echeverri[5] estimate US$4000/kW with potential for future schemes to reduce to below US$3000/kW. While it is believed that the ISORCC costs considered in this simple study are very conservative, it does suggest that the gas turbine should not be operated at levels below 75% load, and preferably around 90% load to achieve a US$3000/kW level.

6.5 Levelized Cost Of Electricity (LCOE)

Unlike a stand-alone CSP plant, an ISCC or ISORCC plant consumes fuel. Whereas capital costs dominate for a CSP plant, the cost of fuel has a major impact in the LCOE calculations for ISORCC and ISCC configurations.

Using the assumed capital costs and predicted plant performance derived in the previous sections, the LCOE was calculated for both the high and low DNI cases for three different fuel costs. The assumptions for the LCOE calculations are given in Table 1.

Debt/ Equity Ratio	Tax Rate (%)	Weighted Average Cost of Capital (%)	Project Lifetime (years)	Operating Hours per year	Plant Avail-ability (%)
70/30	30	10	20	8500	97

Table 1: Finance assumptions for LCOE calculations

The operating hours and plant availability are high for an ISORCC plant as they are primarily determined by the gas turbine. Alqahtani and Patino-Echeverri[5] advise a gas-fired CCGT should achieve LCOEs in the range 4.8c/kWh to 13.8c/kWh when natural gas prices are in the US$4 to 18/mmBtu range, and that ISCC should be competitive with CCGT for higher gas prices. The estimated LCOEs for this simple ISORCC study are shown in Figure 12 for the different gas turbine loads considered

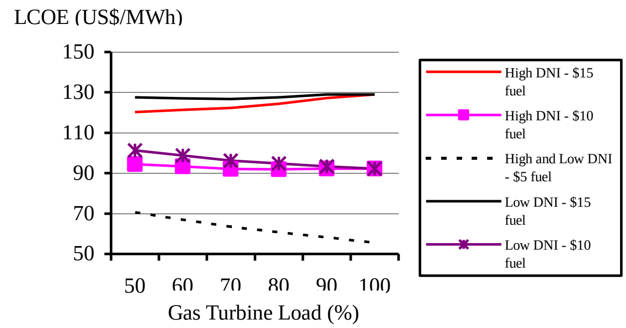

Figure 12: Estimated LCOE in US$/MWh for a 35 MW ISORCC plant for varying gas turbine loads (calculated on a 40°C ambient temperature basis)

Figure 12 illustrates that for a low cost fuel, adding a solar component has a negative impact on the LCOE, whereas a positive impact can be seen on the high fuel cost case. For the medium fuel cost case (US$10/mmBtu), operating the gas turbine down to about 75% to 80% load appears to offer a benefit, but then the additional cost of the larger solar field required for lower part load operation starts to negatively influence the LCOE.

The calculated LCOE is below the levels indicated in the IRENA report[7] for 2011 CSP installations, and in line with their projections for 2020 CSP plants. For fuel costs of US$10/mmBtu and below, the LCOE for this simplified ISORCC plant is in line with the recent bid of US$945/MWh for the 200 MW 4th phase of Dubai's Mohammed bin Rashid Al Maktoum CSP solar park[8], but still above the recent 150 MW Aurora CSP project in Australia which is quoted as having a Levelized cost of just US$60/MWh unless a low cost fuel can be obtained. It should be noted though that the Aurora project attracts a Renewable Energy Certificate worth A$50/MWh and it is unclear as to how this revenue has been factored into the US$60/MWh bid price.

It should also be noted that in the above paragraph, the LCOE for a small, distributed power plant is being compared to that of a large scale CSP. A better comparison may be against existing price levels in countries with small grids and low installed power generation capacities which rely on imported fuel oil. Piantini and Janson presented some residential price tariff for Caribbean nations at a recent Waste to Energy conference11 which shows residential power prices for counties dependent on imported fuel oil as high as $0.37/kWh (Figure 13). An ISORCC plant fueled by imported LNG or LPG producing power at US$130/MWh would certainly offer competitively priced electricity in such countries, while simultaneously providing a large reduction in both CO_2 and pollutant emissions.

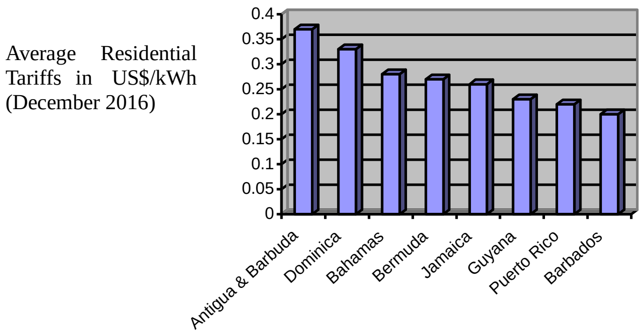

Figure 13: Average Residential Tariffs for selected Caribbean nations, December 2016 (Piantini & Janson, see reference 11)

To double-check the potential competitiveness of ISORCC, a basic sensitivity analysis was run for the US$5/mmBtu and US$10/mmBtu fuel cost cases by decreasing the calculated efficiency of the plant by 10% and increasing the total capital cost by 20%. The results showed a range of LCOEs between US$62/MWh for the high DNI, low fuel cost case to US$116/MW for the low DNI, medium fuel cost case. This would indicate that even if the cost original assumptions, which were believed to be somewhat high to start with, were actually too low, than the LCOE from an ISORCC scheme would still be competitively priced with that from stand-alone CSP or small-scale CCGT.

6.6 Fuel Savings and CO_2 Reduction

None of the LCOE calculations factor in any cost of carbon or renewable incentives that might benefit the ISORCC.

Comparing the studied 35 MW ISORCC plant with a high DNI, with gas turbine turn-down to 50% load, to the natural gas-fired equivalent without the solar contribution, the daily gas consumption is calculated to drop from 1,850 MWh to 1,662.7 MWh, a daily saving of 187.31 MWh (639.09mmBtu). This equates to a 10.1% reduction in fuel consumption and 12,750 tonnes per year less CO_2 emissions. With a cost of fuel of $10/mmBtu, the annual fuel savings for 8,500 hours operation are US$2.33 million.

Including thermal storage could increase the potential fuel cost and CO_2 savings for the appropriate operating profile. If the operating profile is expected to be something similar to that shown in Figure 2, then solar energy produced during the peak production hours in the afternoon can be stored and released for the early evening peak. This would allow the gas turbine power output to be reduced so that the gas turbine and ORC could cover up to around 75 to 80% of the maximum forecast demand with no solar input, using ‘surplus’ solar power to meet peak demand.

6.7 Future studies

It is clear that this is a very simple study, which was undertaken purely to illustrate whether ISORCC could produce electricity at an installed cost that was competitively priced and at a competitive installed cost compared to stand-alone CSP. Now this has been ascertained, more detailed studies are required to examine how ISORCC performs under different operating scenarios, with more accurate modelling of the ORC performance under part-load conditions when there is a low heat contribution from the solar field.

To this purpose, Siemens have engaged TU Delft to study three ISORCC power plant configurations, ranging from 40 MW to 85 MW in output, with four different operating scenarios. While this simple study assumed parabolic trough collectors with thermal oil as the HTF, this new study will examine the impact of using different solar thermal collector technologies, such as linear Fresnel collectors, which may have a positive impact on both plant cost and performance. The new study will also examine the impact of thermal energy storage on the project economics. Further studies may include more accurate modelling of the plant to take into account daily variations in solar collector efficiencies and ambient temperature variations.

7 CONCLUSIONS

As the electricity generation sector moves into new operating regimes for fossil fuel power plants to provide the flexibility and stability which grid operators require, it is clear that hybrid solutions are one very interesting potential concept to help resolve the issues faced by the industry.

The world has an abundance of solar resources and solar/fossil fuel hybrids offer a flexible, dispatchable and economic solution to overcome the problem of intermittency of conventional solar power generation while simultaneously reducing the overall carbon footprint of power generation.

The aim of this study was to make an initial assessment as to whether ISORCC could provide an economically viable hybrid solution to address the market challenges at distributed power scale. From the analysis, ISORCC appears to offer a competitive ‘zero water’ solution, which could be applied to many countries and regions around the world, while offering enhanced flexibility compared to a conventional ISCC. The results presented indicate that further more detailed studies are justified.

The ability to integrate multiple heat sources into a single system, and incorporate heat storage, while allowing each system to operate independently of the others, provides an enhanced flexibility as well as providing the opportunity to optimize plant designs for the specific operating profile foreseen to maximize efficiency and cost. The operation of the gas turbine at part-load not only increases overall plant fuel efficiency, but also allows the gas turbine to instantly respond to any change in energy output from the solar field, ensuring the power demands can be met with no break or unacceptable dip in supply voltage or frequency.

The economic calculations indicate that ISORCC would be competitive compared to stand-alone solar power plant. While some areas in the analysis need to be refined and evaluated in greater detail, there are some areas identified already where cost savings or performance enhancements could be made by evaluating alternative technologies to those considered here. The authors believe that a more comprehensive and detailed analysis would show an improvement in the competitiveness of ISORCC.

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APPENDIX 1: ISORCC PERFORMANCE AND COST CALCULATIONS

Introduction

The following calculations assume a site at sea level, a constant ambient temperature of 40°C and are based on a the nominal performance of a Siemens SGT-750 operating on natural gas fuel.

Assumptions
ORC turbo-generator gross electrical efficiency: 20%
Solar collector efficiency: 50%
Additional Solar Field heat losses: 10%
Solar Field cost: US$255/$m^2$
Annual plant operating hours: 8500 per year
Annual average DNI:
High Case: 2700kWh/m^2
Low Case: 2100kWh/m^2
CO_2 emissions: 53.07kg/mmbtu

Heat Input Required from Solar Field

Power Plant Output (kW)	35820	35820	35820	35820	35820	35820
Gas Turbine Load (%)	100	90	80	70	60	50
Gas Turbine Output (kW)	28290	25460	22630	19800	16970	14140
Required ORC power output (kW)	7530	10360	13190	16020	18850	21680
Heat Input required by ORC (kW)	37650	51800	65950	80100	94250	108400
Heat Input to ORC from Gas Turbine (kW)	37650	32780	30829	28689	26749	24797
Heat Input to ORC required from Solar Field (kW)	0	19020	35121	51411	67501	83603

Solar Field Size

Gas Turbine Load (%)	100	90	80	70	60	50
Heat Output required from Solar Field (kW)	0	19020	35121	51411	67501	83603
Annual Heat Input to Solar Collectors (MWh)	0	179633	331698	485548	637510	789584
Solar Field Size: High DNI (m^2)	0	133012	245612	359532	472054	584660
Solar Field Size: Low DNI (m^2)	0	171079	315903	462427	607152	751985

Plant Costs – High DNI Case

Gas Turbine Load (%)	100	90	80	70	60	50
Solar Field Cost (US$ million)	0	34	63	92	121	150
Power Plant Cost (US$ million)	70	74	77	81	88	93
Total Costs (US$ million)	70	108	140	173	209	243
Installed Cost (US$/kW)	1955	3020	3920	4828	5824	6789

Plant Costs – Low DNI Case

Gas Turbine Load (%)	100	90	80	70	60	50
Solar Field Cost (US$ million)	0	44	80	118	155	192
Power Plant Cost (US$ million)	70	74	78	81	88	94
Total Costs (US$ million)	70	118	158	199	243	286
Installed Cost (US$/kW)	1955	3291	4420	5561	6787	7981

Power Plant Performance

Power Plant Output (kW)	35820	35820	35820	35820	35820	35820
Gas Turbine Load (%)	100	90	80	70	60	50
Gas Turbine Fuel Input (kW)	77084	71317	65594	60182	55277	50500
Gross Efficiency (%)	46.5	50.2	54.6	59.5	64.8	70.9

Fuel and CO_2 savings

Assuming the solar energy is produced in line with the fixed installation curve shown in Figure 8, with 100% solar production equating to 50% gas turbine load, zero solar production equating to 100% gas turbine load with a linear relationship for intermediate solar production and gas turbine loads:

Daily Power Generation:	859.7MWh
Daily Fuel Consumption – no solar input:	1850MWh
Daily Fuel Consumption with solar input:	1663MWh
Daily Fuel Saving:	187MWh
Average daily gross power plant efficiency:	51.7%
Annual CO_2 savings	12758 Ton