PRELIMINARY INVESTIGATION INTO THE CURRENT AND FUTURE GROWTH AND AFFORDABILITY OF ORC ELECTRICITY GENERATION SYSTEMS

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ABSTRACT

The Organic Rankine Cycle (ORC) provides a way to produce power from heat resources that are at too low of a temperature to be competitively converted using steam-Rankine cycles. While ORC systems using geothermal, biomass, waste-heat, and solar resources currently provide less than 0.1% of worldwide electricity generation, their market growth has been historically steady, with new resource opportunities helping to marginally increase the installed capacity growth rate in recent years. This paper explores the current growth of ORC electricity generation systems, the theoretical limit of their future growth, and to what extent a policy-based market change will push ORCs towards meeting this potential.

The results from a survey of ORC manufacturers are presented, looking into the prevalence of existing ORC systems and the heat resources which they use. Estimates for the potential for future growth are made based on existing literature, and this is compared with current development. The historic trend for the growth of ORC generation capacity is presented, and it is proposed that if the low current annual growth rate continues, then ORCs are unlikely to become a globally significant energy conversion technology at current electricity demand levels.

The final part of this paper looks at the competitive advantage that ORCs get from GHG pricing, a non-technological factor that affects the growth rate of installed capacity. It is concluded that a truly significant penetration of ORC generation into the global energy mix would require a step change in the amount of resources that can be affordably developed; either through the introduction of new ways to cheaply access and convert resources, or through a massive shift in expenditure on energy systems, which may be unfeasible in future economic scenarios.

1. INTRODUCTION

From the 1970s until the mid 2000s, ORCs were primarily developed in order to generate electricity from geothermal resources in larger systems called ‘binary’ plants. Over the past decade, ORC systems have also started to be applied commercially to biomass and industrial waste heat resources, generally in regions with high electricity prices and subsidies directed at moving away from reliance on fossil fuels. During this time, the number of commercial suppliers of ORC systems has grown, improving the technology and increasing market competition. More recently, solar energy has also been collected and used in commercial ORC installations, as a supplement an existing heat source (Turboden, 2015).

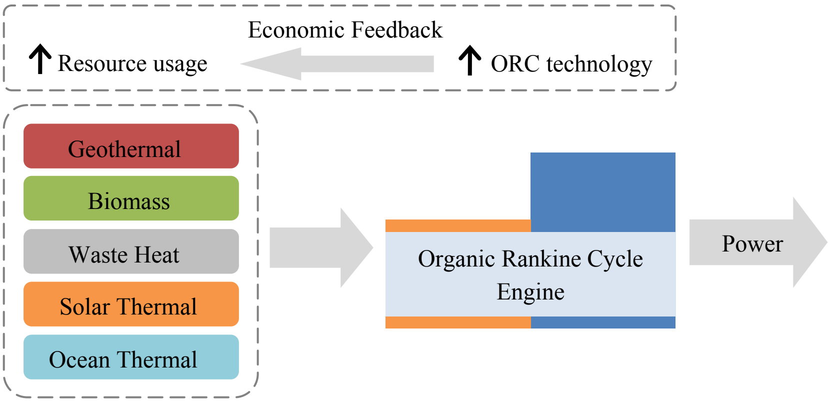

Figure 1: Common ORC resources, and the feedback of an improvement in ORC technology.

The applications for the power generated by ORC systems vary widely, with the majority of systems being used to provide electricity generation. There is however interest in using ORC systems other applications, such as direct shaft work in industrial plants (Quoilin *et al.*, 2013) and (Tchanche *et al.*, 2011), thereby marginally improving the overall efficiency and removing the need for a generator, which can be a significant cost at smaller scales.

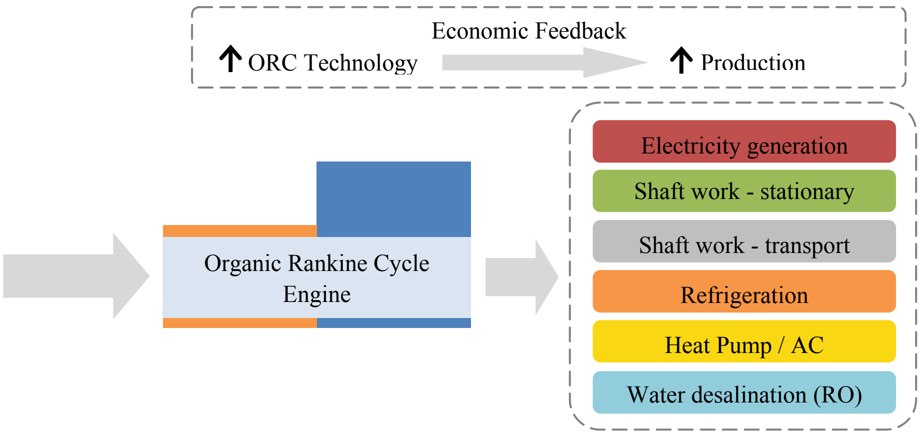

Figure 2: Proposed ORC applications, and the flow-on effect of an improvement in ORC technology.

The use of ORC systems specifically for electricity generation is studied in this paper. A survey of ORC manufacturers was undertaken to estimate the generation capacity currently operating from each ORC resource group. This capacity is compared to estimations in literature for the theoretical global potential of electricity from the heat resources used by ORCs. Lastly, as a factor which influences the growth of ORC technology that may soon undergo global changes, the effect that GHG pricing has on the competitiveness of ORC systems is investigated. These studies are intended to help inform preliminary predictions as to where ORC growth might lead to in future, and conclusions are drawn along those lines.

2. SURVEY OF ORC CAPACITY GROWTH

2.1 ORC Manufacturer Survey

A survey of ORC manufacturers was taken to determine how much generation comes from each resource, and for how long the development of the market for ORC systems has been underway. The size, installation date, and resource used for ORC systems from seventeen leading ORC manufacturers were surveyed. The survey data was gathered from manufacturer's websites and case studies. Only installations still currently in operation were included. The survey is not likely to be exhaustive, especially pertaining to smaller manufacturers of waste-heat recovery (WHR) and biomass units. Systems that utilise heat from biogas burners were classed under WHR.

Table 1: Total installed capacity of ORC systems from 17 major manufacturers, as at the end of 2014. Data from (Exergy, 2015; ORMAT, 2015; Turboden, 2015) and others.

	2014 Capacity (MW)			
Manufacturer	**Geothermal**	**Biomass**	**WHR**	**Total**
ORMAT	1421.9	0	136.0	1558.0
Turboden	19.2	250.6	41.2	311.0
Exergy	122.5	2.4	3.3	128.3
TAS	22.0	0	134.0	134.0
Maxxtec/Adoratec	0	16.5	6.8	23.4
ENEX	105.3	0	0	105.3
Tri-O-Gen	0	0.3	2.6	2.9
Other manufacturers*	4.8	4.7	8.3	17.9
TOTAL	1705.9	275.6	332.8	2160.3

*Other manufacturers include GMK, EXERGY, Opcon, Cryostar, BEP-Europe, Bosch KWK, MANNVIT, ENERTIME, ElectraTherm and UTC.

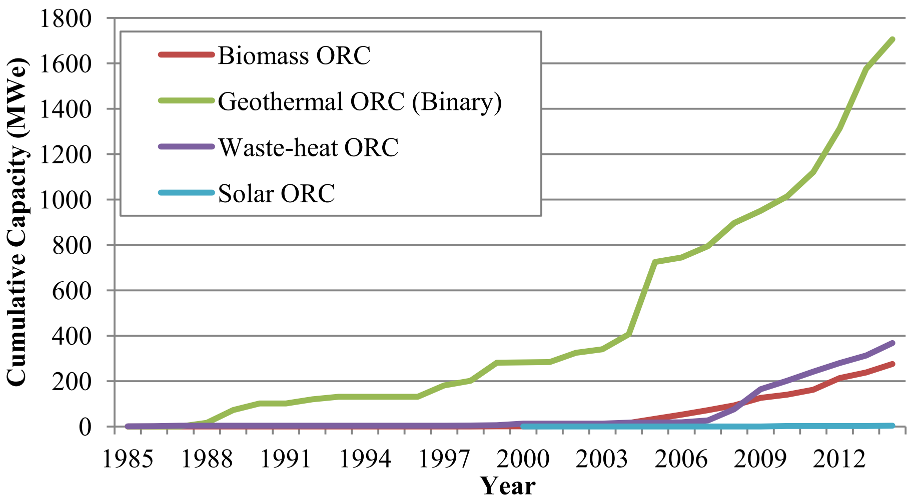

Figure 3: Growth of worldwide electricity generation capacity of ORC systems by resource type.

Figure 3 shows that geothermal ORC (binary) plants account for the majority of installed ORC capacity, with a significant amount of generation having been installed from the late 80's onwards. In 2014, binary ORC systems accounted for about 20% of total geothermal generation (IEA, 2014). Biomass and WHR-ORCs have emerged more recently, with global capacity starting to grow from the mid 2000's. The shape of the capacity growth curves indicate that ORC systems have undergone faster growth over the decade since 2005, which could perhaps be attributed to technology developments and the increasing price of other means of electricity production (IMF, 2015).

Table 2: Percentage generation capacity and average unit size from survey.

Heat Resource	**Percentage of Total ORC Capacity**	**Max Unit Size** (MW)	**Min Unit Size** (MW)	**Average unit size** (MW)
Geothermal	71.4	95	0.2	13.3
Biomass	13.1	8.0	0.07	1.1
WHR	15.3	5.3	0.0006	0.8*
Concentrating Solar**	0.2	2.0	0.1	0.9

*Excluding numerous very small (0.5 – 15 kW) gas pipeline compressor waste heat systems
** 2MW of concentrating solar generation is from an industrial waste heat/solar hybrid plant.

The survey results show that geothermal ORC systems are on average an order of magnitude larger than ORCs operating from other resources. Biomass, WHR and concentrating solar systems are of a similar average size, but the smallest commercial biomass and solar plants are currently much larger than the smallest WHR systems. This might be due to the additional equipment required to supply and transform biomass and solar resources (such as a boiler system), whose costs do not scale well to smaller sizes. Development is currently underway to commercialise smaller, domestic-scale biomass and solar powered cogeneration (heat and power) systems (Jradi and Riffat, 2014; Qiu *et al.*, 2012; Quoilin *et al.*, 2015).

2.2 Global capacity limit of ORC production

An important factor into whether the current ORC growth rates shown in Figure 3 can be expected to continue is the size of the available remaining resources, and at what price these resources can be utilised. Investigations relevant to the maximum practical potential, or capacity ceiling, of the development of energy resources using ORC systems are explored, and compared with current worldwide demand. These investigations are also presented in greater depth in (Southon, 2015).

2.2.1 Geothermal: In a study by (Ungemach, 2010), geothermal resources have been estimated to be able to provide a widely ranging potential of 70 GW to 2000 GW electrical capacity, depending on weather Enhanced Geothermal Systems (EGS) can be economically employed. A study by GNS science New Zealand also estimates that geothermal production could potentially reach to around 2000 GW using EGS systems (Chris J. Bromley & Ragnarsson, 2010). If about half of these systems were to use ORC energy conversion technology, an increase from around 20% currently, then a theoretical production capacity of 35 – 1000 GW, or 1.0 – 29 EJ per year assuming a 92% capacity factor, would be able to be provided using geothermal-ORC (binary) systems.

2.2.2 Biomass: It is apparent that a large expansion of biomass-ORC electricity production would be possible if ‘biomass – dedicated electricity’ systems were to become cost-effective; i.e. installations where biomass was produced for the sole purpose of electricity production. Estimates for the maximum potential of electricity generation through this means vary across a large range. In a review study by (Heinimo & Junginger, 2009), estimates for the additional thermal resource potential from managed biomass by 2050 were found to lie between 40 – 1100 EJ per year, with the higher side estimates assuming maximum land use change and technological advancements, particularly in agriculture. The IEA indicates that the annual energy production from biomass is currently around 46.6 EJ/yr (IEA, 2014). If all current and theoretical potential biomass resources were to be combusted in an ORC cycle with a net thermal efficiency of 20%, this would result in a potential production of 17.3 – 229.3 EJ of electricity annually, or an equivalent capacity of 610 – 8070 GW at a 90% capacity factor.

2.2.3 Waste-heat recovery (WHR): The potential for low-grade waste heat recovery using ORCs is small when compared with Biomass or Geothermal, as the resource is limited to industrial heat sources existing at the time. A survey of the low and high grade industrial waste heat recovery potential for the UK (McKenna & Norman, 2010) estimated that 36 – 71 PJ of heat was available to be recovered annually, although the authors indicated that this estimate is probably lower than the real value. If the high-side estimate for recoverable heat were to be converted by ORC systems with an average net thermal efficiency of 18%, 13 PJ of electricity could be produced annually. This figure is around 1% of the UK’s annual electricity generation of 1374 PJ in 2010 (OECD/IEA, 2015). If it is assumed that the worldwide proportion of recoverable waste heat to electricity generation is the same as for the UK, and that the global quantity of industrial waste heat remains unchanged into the future, then WHR using ORCs could mitigate an estimated maximum of 837 PJ annually, or 1% of current world electricity demand.

2.2.4 Solar: There have been many studies into the theoretical potential of solar electricity generation, with variations of up to nearly two orders of magnitude, depending on the assumptions used. For instance, a study using worldwide geographic data and stringent land-exclusion criteria estimated solar to have a massive 830 EJ per year electricity potential, many times greater than current

worldwide electricity demand (Trieb *et al.*, 2009). Other studies estimate a much smaller potential, such as 16.5 – 43.5 EJ (assuming a 30% capacity factor) in a study by (Castro *et al.*, 2015).
While it is likely that the majority of CSP growth will be met using steam-Rankine conversion technology, it is possible that the cost of high-temperature collectors may cause ORC systems to become more dominant going forward (Zarza, 2013). Rooftop thermal solar-ORC systems are also currently being investigated, due to their potential ability to work as a domestic heat pump in reverse operation (Quoilin *et al.*, 2015). From initial studies, these systems appear to provide a roof area-to-electricity conversion density of about ¼ that of an equivalent solar-PV system, as the energy collected is also used for heating purposes. In general, the theoretical potential energy yield of solar-ORC systems appear to be similar to that of biomass resources, but the lower capacity factor of solar generation results in a greater capacity requirement in order to reach this potential. If it is assumed that half of solar collection going forward were to use ORC energy conversion technology (up from near-zero currently), the range of estimates found would require a generation capacity of 870 – 44000 GW at a 30% capacity factor.

2.2.5 Summary of theoretical capacity potentials: Overall, the results of the studies investigated indicate that under a scenario of large-scale EGS development and significant land use change for biomass and solar collection, a significant penetration of ORC technology into the global energy mix is theoretically possible.

Table 3: Current and potential ORC electricity production, and total electricity production using all conversion technologies, from resources utilised by ORCs. Sources (EPIA, 2014; IEA, 2014; IRENA, 2013). Estimates of theoretical ORC capacity based on various studies as summarised in parts 2.2.1 – 2.2.4 of this paper. Further analysis of these studies is available in (Southon, 2015).

Resource	**Current ORC Electricity Production** (PJ/yr)	**Current Electricity Production - all technologies** (PJ/yr)	**Theoretical potential maximum ORC electricity production estimate** (PJ/yr)
Geothermal	50	240	1,000 – 29,000
Biomass	9.1	1,270	17,000 – 230,000
WHR	11.5	11.5*	840
Solar CSP	0.035	36	17,000 – 830,000
Rooftop Solar	0.0	615	
Total	**71**	**2,170**	**36,000 – 1,090,000**
Current worldwide electricity demand			**81,600**

*WHR figure is estimated as for low-temperature and discontinuous high-temperature resources only

The results in Table 3 indicate that there is significant remaining potential for the development of the heat resources used by ORC systems, which are currently developed to between 0.2% - 6.0% of their estimated potential capacity. ORC technology currently is a minority choice of energy conversion technology for geothermal, biomass and solar CSP resources, as the majority of development thus far has used steam-Rankine cycles.

Given the lower values for maximum potential capacity, a complete ‘replacement’ of current electricity generation resources would not be possible through the utilisation of ORC systems and their resources alone. Despite this, these estimates imply that under a scenario of significant land-use change for biomass and solar electricity production, much larger amounts of electricity production might be possible. Geothermal (EGS) and solar resources are estimated to have the largest potential to provide significant generation capacity, with ranges between 21% - 282% and 21% - 1017% of current global capacity respectively.

2.3 ORC capacity at current growth rates

The growth rate of ORCs systems may be impacted by several factors such as policy changes, changes to the price of other means of generation, changes to the demand for electricity, and the maturation of ORC technology leading to lower costs and increased resource access. If these and other factors were to remain unchanged, it could be argued that using past growth trends can be expected to reasonably predict future ORC growth. This may be especially true for the more developed geothermal ORCs, but also to a smaller extent for less mature waste heat and biomass ORC technologies.

Several curve types were fitted to the capacity growth curves in Figure 3. For each curve type, the curve was truncated by earliest year in order to achieve a maximum coefficient of determination (R^2-value), with a minimum period of five years. The R^2-values of the trend lines for each resource are indicated in Table 4.

Table 4: Curve type, fit as determined by the coefficient of determination, and the truncation year necessary in order to achieve the maximum R^2-value for each curve type, for the ORC capacity growth curves shown in Figure 3. The models that best fit each resource type are indicated in bold.

Resource	Curve Fit	R^2	Truncation year
Geothermal	Linear	0.986	2010
	Exponential	0.982	1989
	Power	0.947	2003
	Quadratic	**0.990**	**2005**
Biomass	Linear	0.979	2010
	Exponential	0.989	2009
	Power	**0.998**	**2003**
	Quadratic	0.997	1998
WHR	**Linear**	**0.997**	**2009**
	Exponential	0.947	1975
	Power	0.983	2008
	Quadratic	**0.997**	**2009**

Of the trend lines investigated, the best fits in terms of R^2-value and amount of data covered are an exponential curve fit for geothermal generation from 1989 – 2015, and an exponential fit for WHR capacity from 1975 – 2015. This is because all the ORC resources were found to initially undergo relatively slow capacity growth for each resource, with a higher growth rate having occurred over the last decade, as can be seen in Figure 3. Factors that may have caused this increase in growth are; technology developments enabling access to a wider pool of resources, maturation of ORC technology leading to more technology providers and increased price competition, increasing worldwide electricity prices, increased worldwide electricity demand growth rates and the introduction of subsidies directed towards increasing renewable electricity generation. The omission of ORC systems that are now decommissioned may also have influenced the recorded growth trends.

It could be argued that if further significant changes to these growth factors were not to occur, a further increase in ORC capacity growth rates may not be expected, leading to a more linear trend line going forward. Figure 4 shows a linear curve fit to the to the capacity growth rate of ORC systems seen in recent years, as found from the survey.

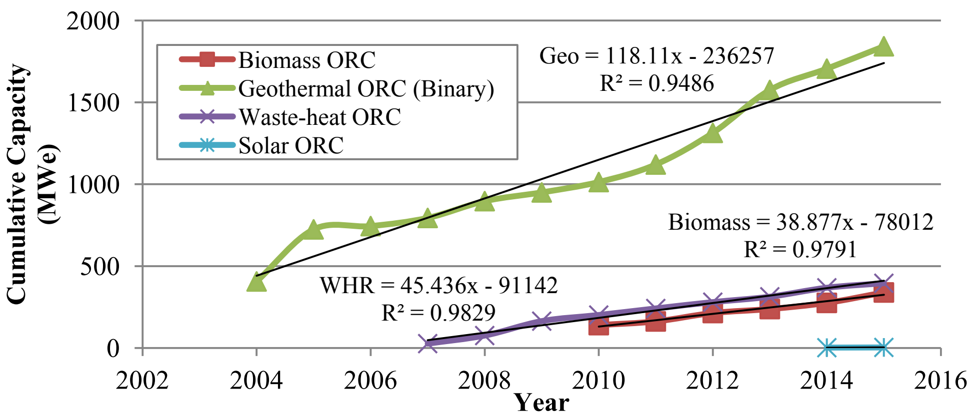

Figure 4: Resource-specific linear capacity growth trends for ORC systems.

The effect of a linear growth trend going forward on the global energy mix is shown in Table 5. Extrapolating the current growth rates using a linear trend line indicates that it will take nearly 150 years before annual electricity generation from ORCs will provide 1% as much electricity as current generation technologies. The years in which ORC systems can be expected to saturate their production potential are also indicated. Table 5 shows that in the year 2657 waste heat (WHR) will be the first resource to become fully saturated, if the resource potential were to remain at its current size.

Table 5: Years in which ORC systems will reach estimated theoretical potential resource limits, and 1% of current worldwide electricity production, if capacity continues to be added at current rates (linear extrapolation). Estimates of resource capacity potential adapted from various studies, as detailed in part 2.2 of this paper.

Resource	Theoretical future potential (PJ/yr)	Assumed average capacity factor	Year when potential capacity is achieved	Year of 1% current worldwide demand
Geothermal	1,000 – 29,000	0.92	2,292 – 69,000	2,238
Biomass	17,000 – 230,000	0.90	17,403 – 210,312	2,746
WHR	840	0.90	2657	2,638
Solar	17,000 – 830,000	0.30	1,058,311 +	52,715
Total ORC	36,000 – 1,090,000	0.88		2,160

3. ORC AFFORDABILITY UNDER GHG PRICING

As mentioned in part 2.3, ORC systems may become cheaper and more competitive through a variety of means, which will impact the rate at which new capacity is installed. As a policy intervention that may undergo changes in the near future with a potentially global influence (Mansell, 2015), greenhouse gas (GHG) pricing is highly relevant to ORC electricity production. GHG pricing mechanisms improve the competitiveness of ORC electricity over fossil-based generation, as a sufficiently large GHG price will incentivise the installation of new renewable generation in favour of established fossil-based systems.

3.1 GHG emissions from ORC energy systems

Selected lifetime-averaged gCO_2e/kWh figures for electricity generation from resources used by ORCs are presented in Table 6, as investigated for the IPCC fifth assessment report in (Schlömer *et al.*, 2014). A separate figure for 'biomass after re-growth' from (Weisser, 2007) is included, as the figure for the fifth assessment report assumes that the biomass fuel is dedicated energy crops or crop residues, and so is not applicable to current biomass ORC installations that often use forest wood. The 'biomass – dedicated electricity' values may become more applicable in the future however if large scale biomass-to-electricity conversion was pursued, as mentioned in part 2.2.2. Binary ORC plants are likely to sit at the lower end of the range of emission intensities given for geothermal, as these generally have higher reinjection rates compared to flash or steam technologies (Glassley, 2014).

Table 6: Estimated lifetime gCO_2e/kWh of ORC resources (Schlömer *et al.,* 2014) and (Weisser, 2007). The WHR-ORC figure has been estimated. The '%' column indicates the relative median emissions intensity for each technology when compared to pulverized coal. The 'cost' column indicates the resulting lifetime-averaged cost in cents/ kWh of an imposed carbon price of \$25/tonne CO_2e.

Commercially Available Technologies	Min	Median	Max	%	¢/kWh
ORC resources					
Geothermal	6	38	79	4.6	0.10
Biomass – dedicated electricity	130	230	420	28	0.58
Biomass after re-growth	35	70	99	8.5	0.18
Concentrated Solar Power	8.8	27	63	3.3	0.07
WHR-ORC (estimated)		20		2.3	0.05
Fossil-fuel plants					
Coal - pulverised burner	740	820	910	100	2.05
Gas - CCGT	410	490	650	60	1.23

As it is not available in literature, a gCO_2e/kWh is estimated for WHR-ORCs. WHR-ORCs have no ongoing fuel costs, and so all of the CO_2 emissions from a WHR plant are embodied in the capital, operation and maintenance costs. As WHR plants generally cost somewhere in between onshore wind power and concentrating solar (Southon, 2015), and as the types of materials required for these systems are somewhat comparable (J.L. Sullivan *et al.,* 2010), the lifetime CO_2e/kWh is estimated to be in the range between these two plant types (1.3%-3.3% of pulverized coal). This estimate is not expected to apply for WHR-ORCs in situations where the process providing the waste heat has to be changed in order to accommodate the heat extraction, such as requiring additional heat or increasing fan power.

3.2 ORC competitiveness with coal electricity under GHG pricing

The cost of producing electricity can be represented using the Levelised Cost of Electricity (LCOE) shown in equation (1).

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \tag{1}$$

Pulverised, scrubbed coal is a major source of electricity worldwide, with a historical LCOE of around \$0.06 / kWh (NREL, 2014). A simple economic model is used to explore the effect of GHG price on the competitiveness of ORC systems compared to standard pulverised coal electricity. The LCOE of theoretical geothermal (binary), WHR, biomass without heat sales, and CSP electricity were modelled using the following assumptions:

- Capacity factors of 92% for geothermal, 90% for biomass dedicated electricity and WHR, and 30% for CSP.
- Annual O&M costs of 5%.
- System lifetime of 20 years.
- Discount rate of 6%.
- Fuel cost for biomass dedicated electricity of \$0.015/kWh.

The lifetime-averaged cost/kWh of a nominal carbon price is then added to this LCOE to give the final electricity cost (LCOE'). The maximum ORC system investment price that still results in a LCOE' less than coal at 6¢/kWh can then be found for each carbon price, shown in Figure 5.

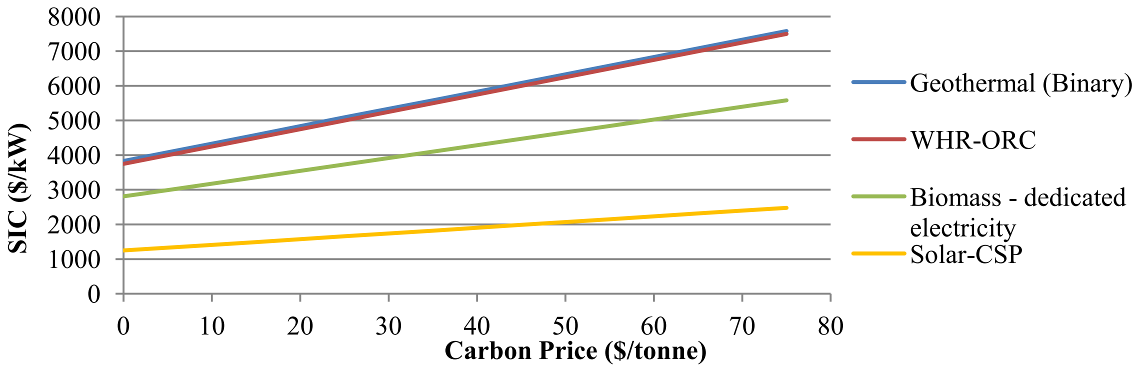

Figure 5: Maximum competitive cost/kW (SIC) for ORC systems in order to have a lower LCOE' than pulverised coal with a base price of 6¢/kWh under various GHG prices.

Figure 5 shows that a carbon price affects the maximum competitive cost of all the ORC system types investigated in a similar way, as they all produce far fewer GHG emissions than coal. At a GHG price of around \$38/tonne CO_2e, an ORC system can remain competitive at an SIC 1.5 times greater than if no carbon price was imposed. If it is assumed that all other technologies remained equal, the worldwide implementation of a policy such as this would increase the ORC capacity growth rate, reducing the time for ORCs to become a significant electricity production technology globally.

CONCLUSION

While ORC systems offer a low-CO_2 electricity solution when compared to energy-dense fossil fuel generation, their current capacity growth rate (from all energy resources) is far from sufficient for ORCs to soon become even a partial (1%) replacement for traditional electricity generation capacity, except in a few local regions and off-grid systems. In order for ORC generation to make a meaningful impact on GHG emissions in the 21^{st} century (assuming no decrease in worldwide electricity demand), the means to affordably access and deliver as-yet-unharnessed energy resources will have to be developed and rapidly deployed.

This study found that ORCs are currently very far from being limited by the theoretical capacity of their heat resources at a global level, and so it is highly likely that there is also substantial room for growth of ORC capacity within many local electricity markets. Of the heat resources investigated, Enhanced Geothermal Systems (EGS) appear to offer the most promise for large-scale new development without having to implement significant land-use change, although many barriers still remain before EGS can fill this role. A carbon price was identified as one mechanism which could make ORCs more competitive; it was found that a GHG price of $38/tonne would enable ORC systems to be competitive with pulverised coal at specific investment costs (SICs) 1.5 times greater than if no carbon price was implemented.

NOMENCLATURE

IEA	International Energy Agency	
EGS	Enhanced Geothermal Systems	
CSP	Concentrated solar power	
GHG	Greenhouse gas	
CO_2e	Carbon dioxide equivalent	
SIC	Specific Investment Cost	
LCOE / LEC	Levelised Cost of Electricity	
LCOE'	Levelised Cost of Electricity including additional carbon price	
I	Total investment outlay	($)
M	Operations, maintenance and repair expenditure	($)
F	Fuel expenditure	($)
E	Energy production	(kWh)
i	Chosen discount rate	(%)
n	System lifetime	(years)

Subscript

t	Reference year

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