SORCE: A DESIGN TOOL FOR SOLAR ORGANIC RANKINE CYCLE SYSTEMS IN DISTRIBUTED GENERATION APPLICATIONS

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Synopsis

Recent interest in small-scale solar thermal combined heat and power (CHP) power systems has coincided with demand growth for distributed electricity supplies in areas poorly served by centralized power stations. One potential technical approach to meeting this demand is the parabolic trough solar thermal collector coupled with an organic Rankine cycle (ORC) heat engine. Much existing research touches on aspects of the underlying physics and mechanics of this technology, but a holistic treatment including economic evaluation is lacking. Design and analysis tools are needed to specify the solar collector and power block configurations for meeting performance and financial targets for a range of applications in disparate environments. In this paper we present the Solar Organic Rankine Cycle Economic (SORCE) model combining semi-empirical multi-physics computation modules for solar resource and site environmental parameter characterization along with optical, thermal and electromechanical performance prediction of trough collectors and ORC systems with technical specifications and costs of standard system equipment. The model is tested with data from experimental solar ORC systems at MIT and deployed in Lesotho, southern Africa (29°12'48.44"S, 27°51'37.36"E). SORCE is available for download[1] as an executable program derived from Engineering Equation Solver (EES) that enables site-specific evaluation of a solar ORC system for performance and cost comparison with alternatives (e.g. wind, solar PV, diesel, etc.).

1 Introduction

The demand for distributed energy supplies is growing globally at an unprecedented rate. In areas of the developing world where service from centralized power stations is unreliable or unavailable, the relatively high cost of power generation using diesel fuel (>$0.50/kWh) or photovoltaic (PV) (>$0.30/kWh) systems has motivated the search for alternatives, e.g. the scaled down solar thermal power plants of this study.

A solar ORC power generation system (Figure 1) is similar to the many steam Rankine solar thermal power plants in operation around the globe, with the exception of scale: an ORC is potentially advantageous well below the range of currently planned commercialized installations. At present the smallest commercial solar thermal plants use the ORC, e.g. the 1 MW Saguaro Solar ORC plant in Arizona, USA. Technical variations employed at a small scale are driven by cost considerations and may include differences in the operating thermophysical regimes, the apparatus geometries and materials, working fluid selection, and system component (heat exchanger and fluid machinery) size and type. Design and analysis tools are useful for specifying the solar collector and power block configurations to meet performance and cost targets. Several investigators have made an economic analysis of a particular ORC system, e.g. [1, 2], but relatively few attempts have been made to create explicit integrated thermo-physical and economic models for an ORC system using some specified or unspecified thermal source [3, 4]. To date no comprehensive general model (including thermodynamic, mechanical, electrical and economics components) for a solar thermal driven ORC, with its unique thermal source fluctuation characteristics, has been developed. To bridge this gap, we introduce here a physical and economic model, called SORCE (Solar Organic Rankine Cycle Economic model), developed in the context of a research scale 3kW Solar ORC for distributed power applications.

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[1] http://web.mit.edu/mso/www/SORCE.exe

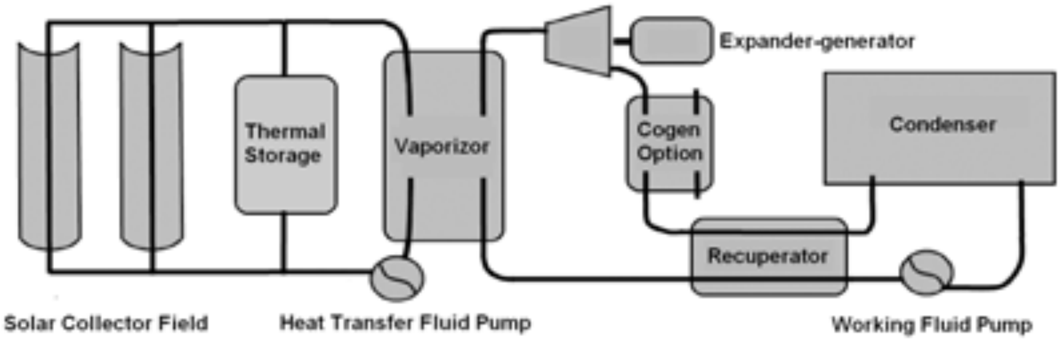

Figure 1: Schematic overview of a representative solar ORC system for distributed power generation.

2 SORCE Model Overview

The main modules in the SORCE model include numerically solved systems of equations for calculating the following:

(1) Available solar energy at a user specified location; and

(2) Its stepwise conversion through optical and thermal apparatus in the solar ORC.

Relevant parameters (Figure 3) are specified via a graphical user interface (GUI) in the diagram windows of Engineering Equation Solver. SORCE modules are based on equations and approaches derived from several literature sources, especially [5], combined with empirical datasets and regressions for phenomena e.g. cloud cover, fluid machinery isentropic efficiency, and generator electromechanical efficiency that are computationally intensive to model. The output of these semi-empirical multi-physics modules are referenced to industry and literature-derived cost data for the specified materials and components, enabling cost assessment on a capital ($) or specific cost ($/kW) basis. In its most basic default configuration, a user of SORCE can specify a location on earth, and the program will calculate the efficiency and power output for a 3kW Solar ORC over an average hour, which is then extrapolated to daily and annual outputs and costs. An advanced user can manipulate the variables in the diagram window to explore alternative configurations of system size, working fluids, temperatures, collector geometries, expanders, etc. and likewise calculate relevant parameters such as performance, cost, and specifications for major equipment (e.g. heat exchange area).

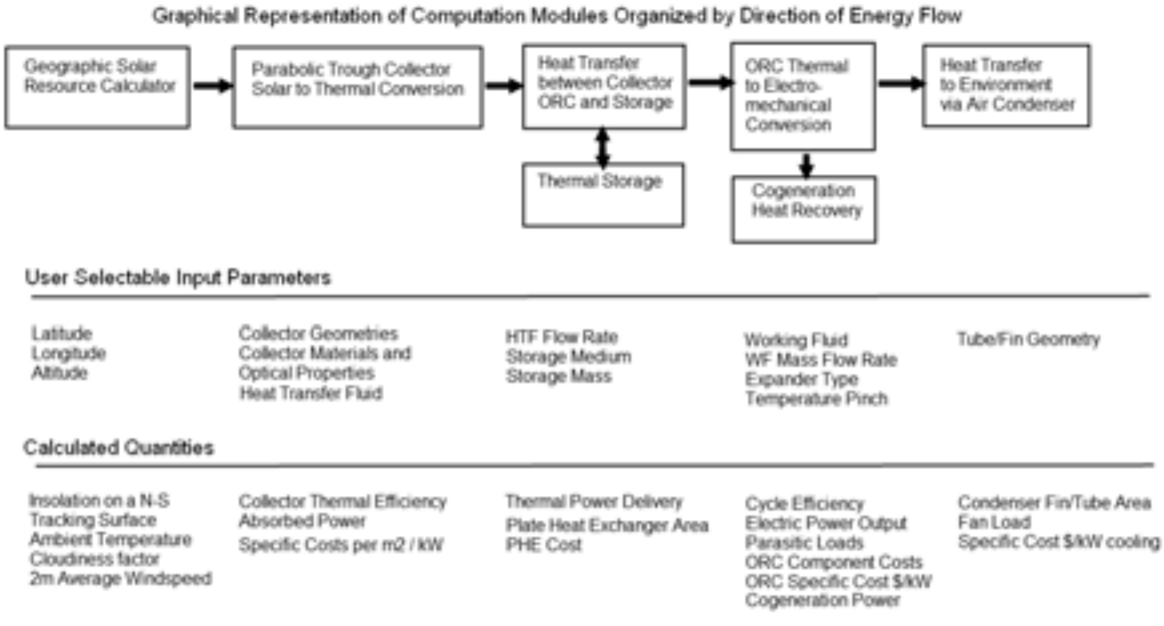

Figure 2: Overview of SORCE model with user input and model output.

SORCE comprises multiple sub-modules that are explained in more detail in the following section. Although EES is a non-ordered simultaneous equation solver, the SORCE program conceptually begins with a solar resource calculation, then passing that information into a solar collector module which calculates a heat gain in a heat transfer fluid. The final node temperature of the collector module is the start node temperature for the storage/buffer module, which creates a temperature profile in the packed bed; the last node temperature of the HTF is the input temperature for the ORC module.[2] The ultimate difference between the ORC output temperature and the initial temperature for the solar collector module reflects the residual in the energy balance indicating whether the storage/buffer unit is charging or discharging.

Finally note that, while SORCE was developed in EES, it is also available for download as a free standalone Windows-executable program online at http://web.mit.edu/mso/www/SORCE.EXE. In addition to the executable program, a detailed document displaying all formatted equations and logic used in SORCE, and listing appropriate references, is available at web.mit.edu/mso/www/SORCE.doc.

3 SORCE Reference System

The SORCE model is intended to be a general and open source platform for calculating the quantities of interest and predicting the performance of a small scale Solar ORC. In practice, the range of design parameters and potential configurations possible in this complex type of system are fairly extensive and a comprehensive model is can only be defined for a system within reasonable limits. SORCE was co-developed in the context of an engineering design process for a prototype 3kW Solar ORC system (Figure 2), and the computational model reflects the major design decisions: e.g. parabolic trough collectors, positive displacement expanders, etc. SORCE can readily be used to explore alternative configurations, however profound departures from the reference case require consideration of implicit assumptions within the system of equations that may be invalidated. In such cases (e.g. alternative concentrator architectures or power block devices, etc.) the program should be altered by the user to model the changes appropriately. The reference system is described in [6] and has the following features:

3kWe Solar ORC prototype

Location – 29°12'48.44"S, 27°51'37.36"E (Pilot Clinic in Berea District of Lesotho)

Solar Collector – 75m^2 single-axis parabolic trough with a 150°C design operating point, using Miro aluminum reflectors and a Heat Collection Element (HCE) with an air-filled annulus between absorber pipe and glazing. Solec Hi/Sorb II selective coating is used on the absorber pipe.

ORC – Two stage expansion of R245fa using modified commercial HVAC compressors with a fixed volume ratio of 2.8, brazed plate heat exchangers for high pressure heat transfer, and commercial HVAC air condenser coils for heat rejection.

Heat transfer fluid (HTF) – Monoethylene glycol (MEG) with thermal buffering in a 2 m^3 thermal storage tank with a packed bed of 19mm quartzite aggregate.

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[2] If the thermal capacity of the packed bed is sufficiently high, and if the heat gain of the solar collector exceeds the heat consumption rate of the ORC, the packed bed effectively acts as a thermal storage system, increasing the daily hours of operation of the ORC and its capacity factor. This feature can be an important design consideration when sizing collectors, storage, and ORC capacities.

Figure 3: Prototype 3kWe Solar ORC in Lesotho, southern Africa, with a 75m^2 40x parabolic trough collector array.

4 SORCE Modules

4.1 Solar Resource Model

The initial task of SORCE is to calculate the amount of beam radiation available to a single-axis tracking (N-S axis) surface at an arbitrary location. Input variables are latitude, longitude, altitude, and time difference (in hours) from GMT. Starting from the solar constant and using well known geometric and trigonometric relationships for the earth's rotation and orbit around the sun [7, 8], the incidence angle and interposing air mass are calculated for the tracking surface on an hourly basis over the entire year. This results in an estimate for annual integrated insolation accounting for absorption in the absence of other (non air mass) atmospheric factors. The latter, particularly cloud cover, is estimated from a NASA meteorological dataset [9] for the specified location, and beam radiation is reduced accordingly. In addition to calculating average direct irradiance (W/m^2) and average duration of daylight (hours), the maximum and minimum beam radiation for the location is available for modeling at the extremes. The module also outputs average wind speed and local ambient temperature for use in computing heat loss in the collector module.

4.2 Parabolic Trough Model

The trough module, largely adapted from Forristall [6], accepts as inputs the minimum, maximum, or average insolation values calculated by the solar resource module. It then primarily conducts a one-dimensional energy balance around a Heat Collection Element (HCE) of user specified dimensions and materials, which is translated to the axial dimension of fluid flow through coupled sequential 1D nodes. Radiation impinges on a reflector element with user input focal length, reflective coefficient, and aperture. The energy is correspondingly reduced (e.g. due to a reflective coefficient < 1) and concentrated onto a nodal area of the HCE, where it is transmitted through a glass envelope and a gas (or vacuum) annulus, and finally absorbed or reflected at the surface of the HCE.

Depending on the absorptivity and emissivity characteristics of the user-chosen selective coating and the temperature of the HTF flowing through the HCE at a given node, some amount of absorbed energy is transferred through the HCE wall into the HTF via the appropriate heat exchange coefficient, calculated from the fluid thermal properties and flow regime parameters. The remaining absorbed heat is lost at the HCE outer surface, via either (1) radiation back through the annulus and envelope to the sky, or (2) convection through the annulus to the envelope, conduction through the envelope, and convection to the ambient air.

This process is repeated for each node, where the input for each node is the output of the previous node, resulting in an overall enthalpy and temperature gain for the focal line length specified by the user. The collector module thus derives a thermal efficiency and outputs a heat flux and temperature gain for the HTF at the user specified flow rate and initial temperature.

4.3 Storage/Buffer Model

The thermal capacity of a small Solar ORC is too low to prevent large temperature swings during insolation transients (e.g. a passing cloud), which can be problematic for stable ORC operation. To overcome this, additional thermal buffering capacity is needed, e.g. in the form of a tank of HTF or, to save on the cost of HTF, a tank partially-filled with inexpensive but high thermal capacity filler material such as quartzite rock. Alternative buffering or storage technologies (phase change materials, concrete, etc.) have been extensively reviewed in the literature [10], however cost is currently minimized with a packed bed implementation.

The essential principle of the storage module is an implementation of the Schumann equations for heat transfer between a fluid and solid matrix, assuming axial plug flow and a timestep equating flow through a single node to the node volume. This is frequently modeled using air as the working fluid [11], however in this case where the HTF is used, the fluid heat capacity term cannot be neglected [12]. Furthermore, the infinite NTU assumption is made, as temperature gradients within bed particles and pore volumes can be neglected for the purposes of establishing a computationally efficient energy balance and temperature profile for a thermally buffered Solar ORC system. The user defines tank geometry, porosity, and the number of nodes to use in calculations. The module accepts the collector final output temperature as the charging temperature, develops the thermal profile during charging, operation, and discharging, and provides an outlet temperature as the implied stable input to the ORC.

4.4 ORC Model

SORCE handles the conversion of heat into electricity in the ORC module according to the structure of the classical Rankine cycle: isobaric heat addition, isentropic expansion, isobaric heat rejection, and isentropic pumping. Real gas properties of the working fluid (the reference fluid is R245fa) are accessed from the internal libraries of EES. The initial process is treated as a 3-zone (superheated, vaporizing, and preheating) transfer of energy in counterflow plate heat exchangers from the HTF into the ORC working fluid with fluid specific correlations [13]. The user selects both the working fluid and mass flow rate (roughly proportional to the desired power output) and establishes the ORC high temperature and degree of superheat, which (in conjunction with the ambient temperature identified in the Solar Resource module) determines the overall energy conversion potential in terms of the Curzon-Ahlborn modified Carnot efficiency [14].

Using the outlet temperature of the storage model as input, the ORC module first calculates the area of heat exchanger necessary for superheat, vaporization and preheating and then determines the heat consumption rate of the ORC and the final HTF output temperature. SORCE allows the user to select the expander unit from a list of HVAC compressor models (from the Copeland ZR family); the fixed volume ratio and displacement of the compressor determines the extractable power and RPMs of the machine. Depending on the specific volume ratio of the working fluid and the operating temperature regime, two stages of expansion may be indicated.[3] The module calculates the thermal state of the working fluid bracketing each process in the Rankine cycle, determines the required area of recuperator (used for recovery of superheated expander exhaust in cogeneration or recycling to the ORC) and air condenser for heat rejection, and imputes the parasitic loads from the condenser fans and from the HTF and working fluid pumps.

Note that dry cooling is currently specified in SORCE as water may be scarce in remote environments where a solar ORC is suitable. As such, commercial HVAC air condensers are integrated into both the reference system and SORCE model [15]. A subroutine calculates the pressure drop in the vapor manifolds as a function of length and pipe diameter.

In addition to providing these practical metrics (e.g. heat exchanger areas, manifold diameters, expander-generator ratings, etc.) for sizing and selection of system components, figures of merit are derived including ORC cycle efficiency, net power output, and daily and annual energy production.

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[3] The fluid state across each expansion stage and the displacement of the chosen expander-generator dictates the division of power output between, and RPM and frequency of, each machine. The machines are selected such that these calculated parameters remain within recommended ranges of the compressor ratings.

4.5 Economic Modeling

The cost of the Solar ORC is developed from summation of a set of equations relating the costs of individual components to a relevant physical parameter, e.g. focal line length or heat exchanger area. These equations represent the components forming the largest fraction of systems costs and are either regressions or linear relationships derived from a bill of materials from the reference system (under construction in southern Africa) or data from manufacturer quotations. Most system components (compressors, reflective sheeting, structural steel, heat exchangers, etc.) are globally standardized products with a cost function reflecting underlying commodity prices (i.e. steel, copper, etc.), and it is assumed that these costs will not vary significantly from one location to another. This assumption breaks down as a function of distance from the global supply chain, which will incur additional and difficult to model logistics costs. The labor fraction of the system materials costs is a user defined variable, as labor costs are expected to be extremely site-specific (the value for the reference system is ~0.25).

5 Model component validation

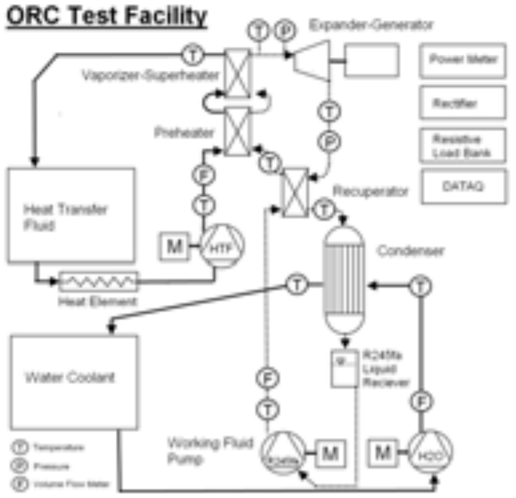


Figure 4: ORC test rig component schematic showing the HTF and working fluid circuits.

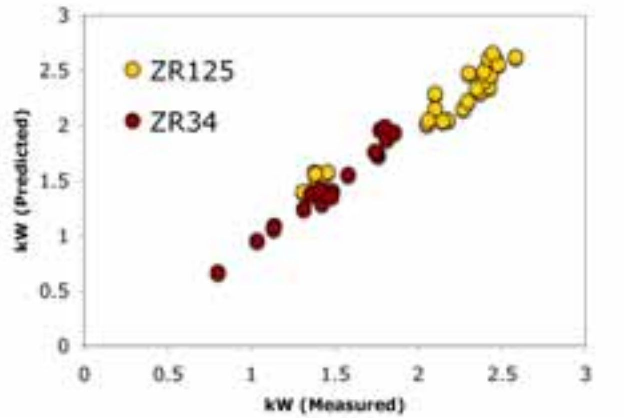


Figure 5: Power output as predicted by SORCE and measured on the ORC test rig. An empirical isentropic efficiency coefficient of 0.815 for the Copeland ZR series was found by minimization of the variance (R^2=0.96) between predicted and measured power under various operating regimes. The coefficient includes the generator derating function.

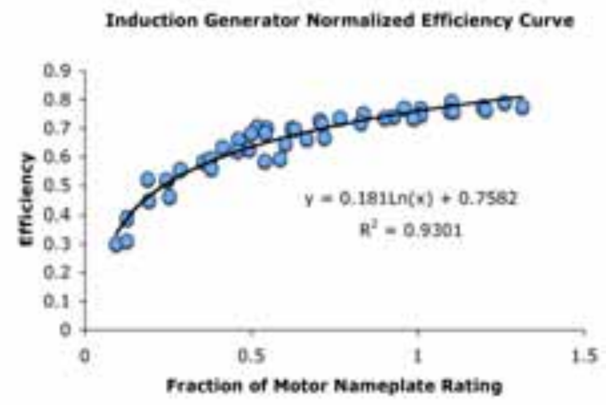


Figure 6: Induction generator efficiency is a logarithmic function of the generator output expressed as a fraction of the motor nameplate rating. The data above represent a 2.2kW 1725 rpm nameplate rated Leeson induction motor.

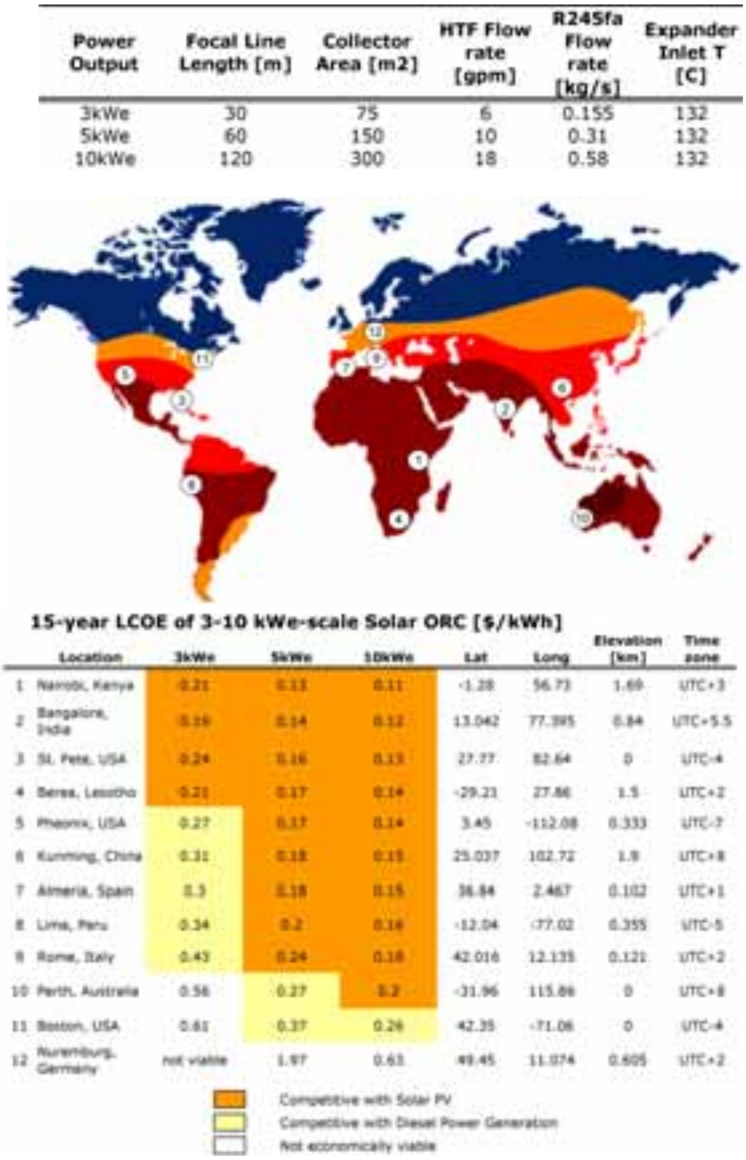
Verification of the results of the global model is pending completion of the reference system in southern Africa; however, many aspects of SORCE have been experimentally tested at the module and component level. In particular, the model is very sensitive to parameters used for fluid machinery isentropic efficiency. The default parameters are derived from component testing at an experimental ORC facility installed at MIT (Figures 4 and 5), described in more detail in [6]. Likewise, induction generator performance for a representative machine has been characterized using a dynamometer facility at MIT's Laboratory for Electromagnetic and Electronic Systems (Figure 6).

Solar resource estimation is currently being validated by heliometer measurement at test sites in St. Petersburg, FL and Lesotho, southern Africa. Daily and monthly high insolation levels to date appear consistent with the model, however a full year of measurement may be required to validate the annual cloudiness factor correction used, currently derived from remote sensing methodologies.

While to date we have limited field results for the collectors used in the reference system, the collector module in SORCE was derived from the extensively validated model by Forristall using the SEGS plant parabolic troughs, and is in general applicable to other collector configurations. Testing on the thermal storage model will seek to establish the validity of the simplifying assumptions, especially neglecting radial dispersion and edge effects for the sake of computational efficiency.

6 Cost and Performance outputs for selected SORCE configurations

Preliminary results from SORCE at its current level of validation indicate specific costs (a 15 year Levelized Cost of Electricity (LCOE)) for the 3kWe reference system of under $0.25/kWh, which compares favorably with PV systems. Comparison of SORCE results for the reference system in selected locations, in 3-, 5-, and 10-kWe configurations, are shown below (Figure 7).



Power Output	Focal Line Length [m]	Collector Area [m2]	HTF Flow rate [gpm]	R245fa Flow rate [kg/s]	Expander Inlet T [C]
3kWe	30	75	6	0.155	132
5kWe	60	150	10	0.31	132
10kWe	120	300	18	0.58	132

15-year LCOE of 3-10 kWe-scale Solar ORC [$/kWh]

	Location	3kWe	5kWe	10kWe	Lat	Long	Elevation [km]	Time zone
1	Nairobi, Kenya	0.21	0.13	0.11	-1.28	56.73	1.69	UTC+3
2	Bangalore, India	0.19	0.14	0.12	13.042	77.395	0.84	UTC+5.5
3	St. Pete, USA	0.24	0.16	0.13	27.77	82.64	0	UTC-4
4	Berea, Lesotho	0.21	0.17	0.14	-29.21	27.86	1.5	UTC+2
5	Phoenix, USA	0.27	0.17	0.14	3.45	-112.08	0.333	UTC-7
6	Kunming, China	0.31	0.18	0.15	25.037	102.72	1.9	UTC+8
7	Almeria, Spain	0.3	0.18	0.15	36.84	2.467	0.102	UTC+1
8	Lima, Peru	0.34	0.2	0.16	-12.04	-77.02	0.355	UTC-5
9	Rome, Italy	0.43	0.24	0.18	42.016	12.135	0.121	UTC+2
10	Perth, Australia	0.56	0.27	0.2	-31.96	115.86	0	UTC+8
11	Boston, USA	0.61	0.37	0.26	42.35	-71.06	0	UTC-4
12	Nuremburg, Germany	not viable	1.97	0.63	49.45	11.074	0.605	UTC+2

🟧 Competitive with Solar PV
🟨 Competitive with Diesel Power Generation
☐ Not economically viable

Figure 8: SORCE model results for levelized cost of electricity (LCOE) using small solar ORC plants in the 3-10kWe size range at different locations. Both size and relative insolation play a role in determining overall specific costs.

In this comparison of power rating configurations across geographic locations, it is possible to see the effect of both insolation variance and system scale on LCOE. While an increase in insolation not surprisingly corresponds to a decrease in specific costs, the magnitude of the effect of scale is less intuitive and seems to be very significant. Other figures of merit (footprint, efficiency, etc.) can be compared across locations, and the physical characteristics of the systems themselves (collector geometries and materials, ORC operating conditions, etc.) can be manipulated in the model to achieve the desired simulation of planned or existing solar ORC systems. In general, results from SORCE indicate that the solar ORC approach can be cost competitive with diesel-fuel based generation and with photovoltaics in areas of high direct normal irradiance (DNI). Although lower sunlight to electricity conversion efficiencies (~ 5%) necessitate greater land requirements in comparison with PV, this may not be a constraint in remote areas. The benefit of cogeneration implicit in solar thermal power may also promote Solar ORC technology as an approach to distributed generation. The current default role of recuperated heat in SORCE is recycling within the ORC, but this heat quantity could alternately be delivered to domestic hot water, heating, or absorption cooling end uses.

7 Summary

New configurations of solar collector and heat engine technologies (e.g. a Solar ORC) can be adapted for distributed generation applications. SORCE is a computational design framework relating the fundamental physical and economic parameters for small scale solar ORC plants to facilitate project design, evaluation, and decision-making. SORCE is available for download from http://web.mit.edu/mso/www/SORCE.EXE as an open-source code Windows executable program, containing a built-in Engineering Equation Solver (EES) engine for site-specific evaluation and cost comparison with alternatives (e.g. wind, solar PV, diesel, etc.).

8 References

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