

Techno-Economic Assessment of a Low-Temperature Solar Organic Rankine Cycle System



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Executive Summary

For the last couple of years, Photovoltaics (PV) has been the preferred choice of technology for harnessing solar energy as against Concentrated Solar Power (CSP). The major issue bogging down CSP is that it is not economical as compared to PV. Emerging technologies such as $s\text{-CO}_2$ and Organic Rankine Cycle (ORC) could be the saviour for CSP going forward. To understand the techno-economics of a solar-ORC system, CSTEP and Indian Institute of Science (IISc) under SERIIUS project, worked together in assessing a low-temperature solar ORC system for off-grid applications. Such a system is assessed for an Indian scenario so that we can thoroughly understand the challenges for economic viability of such as system.

Chapter 1 sets the stage for this report, where we cover the motivation, objective and literature survey for solar-ORC systems. The literature survey includes a thorough review of ORC sub-components and a brief overview on the ORC market. Literature survey shows that small scale ORC systems are quite challenging to operate and there are very few manufacturers of such as system at these scales. The major ORC sub-component which is at the centre of research activity is the expander. Designing an efficient small scale expander is the quite a challenge that the research community is currently addressing.

It is imperative that we fully understand the solar-ORC system configuration before we could perform techno-economic analysis. Chapter 2 describes in detail the various sub-components of a solar-ORC system. The costs, technology options and pros and cons of each of the sub-systems are covered in this chapter. Parabolic Trough Collectors (PTCs) are the preferred technology for harnessing solar energy as they are commercially mature. Glycol based HTFs are cost competitive and hence are attractive for a low-temperature operation. Reinforced concrete looks ideal for Thermal Energy Storage (TES) material as it is stable at low-temperatures and is also inexpensive. With regard to ORC expanders, the choice depends on the source type and the scale of the plant. There are no optimal choice of working fluids for ORC systems and it depends on a number of parameters.

In Chapter 3, we dive into the details of the solar-ORC techno-economic model which we developed for performing analysis. This chapter covers the logic behind energy apportionment and the working of the financial model. The major assumptions for the model are also stated along with the technology options considered.

The results for a low-temperature solar driven ORC system located in Jodhpur are presented in chapter 4. The model was executed for varying Solar Multiples (SMs) and TESs and the configuration which resulted in the lowest LCOE was chosen as the most optimal. We found that the solar to electric efficiency of ORC system peaks at optimal SM (or LCOE). The LCOE was found to reduce with increasing TES capacity but capital cost also increased at the same time. Solar field contributed maximum towards the capital cost of a solar-ORC system. This chapter ends with cost reduction potential for ORC systems to be cost competitive. We observed that local manufacturing of imported components through technology transfer will bring down the LCOE.

Even with a low cost configuration, we saw that the solar-ORC systems are still not cost competitive as compared to other options. This report concludes with chapter 5, where with suggestions on possible options for system to be made economically viable.

Chapter 1 - Introduction

1.1 Motivation

Organic Rankine Cycle (ORC) is a low temperature organic working fluid based Rankine cycle. Rankine cycle is one amongst the idealised thermodynamic cycles which convert thermal energy to mechanical work. A heat engine is used to perform this cycle which involves phase change of the working fluid (the fluid which carries thermal energy). The cycle uses organic fluids because they can undergo phase change at low temperatures. This allows a power plant to generate electricity using a low-temperature thermal energy source. Therefore, an ORC system is suitable for off-grid application where electricity can be generated from waste heat or from renewable energy sources (Tocci, 2017) (or low-temperature sources). Certain remote and rural areas in India are not yet connected to a centralised power grid, resulting in an uneven power supply and severe power outages. India is blessed with good solar energy resource and a decentralised small-scale ORC system powered by a low temperature Concentrated Solar Power (CSP) can help mitigate the problem of sporadic power supply. According to Orosz (2009), a small-scale ORC integrated with CSP could be competitive with diesel generators and Photovoltaics (PV) in terms of Levelised Cost of Electricity (LCOE).

1.2 Objective

As mentioned previously, ORC is a potential solution for off-grid systems in rural India. Keeping this in mind, CSTEP, Massachusetts Institute of technology (MIT) and Indian Institute of Science (IISc) collaborated to identify a low-cost solar ORC system and perform a techno-economic analysis (TEA) on it. The TEA would study the economic viability of the identified system and recommend improvements, if required. The model thus developed would help stakeholders, such as researchers and policymakers, to perform a pre-feasibility analysis for the proposed ORC system configuration.

1.3 Literature Review

ORC technology is mature enough for MW-scale systems, but it is not yet technically and economically viable for smaller systems (1–100 kW) (Tocci, 2017). To make such small-scale systems cost-competitive, several practical challenges have to be addressed, such as high capital and maintenance costs of solar field components and high cost or unavailability of small-scale power blocks. The power block consists of a heat exchanger, expander, condenser and a pump (refer Figure 2). The expander is the major component where the conversion from thermal to mechanical energy occurs.

The overall Efficiency is another parameter that has a significant influence on the economics of ORC systems. Systems with higher overall efficiency generate more electricity but are more expensive. Therefore, establishing a trade-off between expenses and efficiency is vital to make these systems commercially viable (Tocci, 2017). Among the many attempts to arrive at the perfect compromise, researchers believe that targeting expanders can be the best approach for economic viability of ORC systems.

Expanders have a major impact on the performance and economics of an ORC system (Tocci, 2017). The characteristics of an ideal ORC expander would be a high cycle efficiency and a low initial investment cost. Unfortunately, highly efficient expanders (such as turbo-machinery) are expensive, and the relatively cheaper ones have a low efficiency (Bao, 2013). Additionally, ORC expanders don't have a generic design; rather, they are customised for specific applications (Quoilin T., 2013).

Figure 1 shows the efficiency of various expander capacities based on technology classification (Tocci, 2017). Irrespective of the technology used, most expanders have a capacity of less than 10 kW. Also, screw expanders have a higher efficiency at higher capacities.

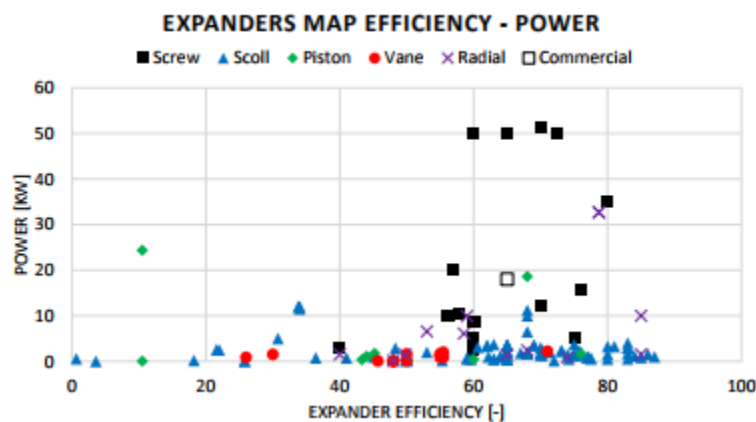


Figure 1. Variations in expander efficiency with power capacity for various expander technologies

Apart from the cost–efficiency compromise, the choice of working fluids is another aspect of an ORC power block that requires careful optimisation. The literature survey shows that a single working fluid cannot perform optimally for all ORC systems (Quoilin T. 2013 & Bao 2013). The optimal choice has to be made carefully as it can significantly affect the performance of the ORC system. Tchanche et al. (2011) have analysed various working fluids for certain solar applications and deduced that R134a (1,1,1,2-Tetrafluoroethane) gives the best performance. A detailed discussion on ORC expanders and working fluids is presented in the subsequent chapters.

Two other components affect the economics of ORC systems to a certain extent: the heat exchanger (HEX) and the pump. As these technologies are fully mature and available commercially, off-the-shelf models are used to lower the initial investment cost (Quoilin T., 2013). Bari et al. (2013) used a commercially available shell and tube type HEX, and the power output increased by nearly 23.7%. Longo et al. (2008) used a standard brazed plate heat exchanger (BPHE), which increased the heat transfer coefficient by nearly 8%. As for pumps, the literature survey reveals that the power consumption varies with the type of organic working fluid considered. According to Quoilin T. et al. (2013), the power consumed by the pumps cannot be neglected and may account for more than 10% of the power produced by the ORC expander.

1.4 ORC Market Analysis

Understanding the ORC market is essential for estimating the efforts required in research and development (R&D). According to Tocci (2017) there is a huge worldwide market for small-scale ORC plants (1–100 kW). We can see some major ORC systems manufacturers listed in Table 1. In spite of the huge market, many manufacturers of MW-range ORC systems (such as Turboden, Ormat and Enertime) have not expanded their operations into small-scale systems yet. This shows that scaling down of ORC systems is quite challenging.

In Table 1, we can also see that most companies use turbo-expanders in their ORC systems (Tocci, 2017). However, when the capacity falls below 30 kW, companies prefer volumetric expanders (Tocci, 2017) (refer section 2.3.1 for more details). Most of the companies listed in Table 1 are still in the prototype-development stage, so prices are likely to reduce once the products are market-ready.

After analysing the market, we can see that suppliers do not yet have reliable systems to meet the growing demand for ORC systems. Hence, there is an urgent need for R&D in this space.

Table 1. List of small-scale ORC plant manufacturers

Company Name	Country	Power (kW)	Expander Type	Heat source T (°C)	Notes
Exergy	Italy	100–240,000	Radial	-	Commercial
Triogen	Netherlands	160	Axial	200 – 300	Expander coupled with the pump: Patent applied
Enogia	France	10–20–40–100	Radial	90 – 160 – 400	Commercial: Turbine coupled with high-speed generator
Rainbow	France	100	Axial	-	Expander efficiency > 80% at 12,000–15,000 rpm
Entropea Labs	United Kingdom	20–300	Radial	400 – 500	Prototype stage
ElectraTherm	USA	35–65–110	Screw	77 – 122	Commercial: Asynchronous brushless induction generator
Zuccato Energia	Italy	30–40–50	Radial	Water T > 94	Commercial: Synchronous generator with ceramic bearings
Infinity turbine	USA	5–50–100	Radial	<110	Working fluid R245fa with magnetic bearings
Pratt & Whitney	USA	80–260	Radial	91 – 149	Working fluid R245fa with 2-pole induction machine
Termo 2 Power	Poland	<300	Rotary lobe	-	Prototype stage: Self-exciting synchronous generator
Calnetix	USA	125	Axial	Low	Expander speed 24,500 rpm; magnetic bearings
Mattei	Italy	3	Vane	80 – 150	-
Rank	Spain	50–100	Radial	85 – 140	Payback period of 2–5 years
EXA	Italy	15–150	Piston/screw	70 – 350	Working fluids R134, R245fa, toluene; induction generator
NewComen	Italy	3–120	-	-	-
Orcan	Germany	20	Radial	550	-
ConPower	Germany	13–75	-	-	Prototype stage
Clean power	USA	77	Scroll	270	Expander speed 1500–1800 rpm; working fluid R245fa

ZE	United Kingdom	95-130	Multistage radial	-	Permanent magnet generator
ICENOVA	Italy	10-30	Eneftech scroll	150	Working fluid R245fa; regenerated cycle
Climeon	Sweden	150	Turbine	70 -120	-
Exoès	France	15	Piston swashplate	-	Transport applications
E-RATIONAL	Belgium	<500	Single screw	105 - 150	Asynchronous generator
Opcon	Sweden	<800	SRM Turbine	250	-

1.5 Report Outline

For a better understanding of solar ORC systems, Chapter 2 provides a detailed explanation of all the major components of such systems. Chapter 3 has a detailed methodology for engineering and financial models of ORC systems. We used these models to perform a techno-economic assessment of an ORC system located at Jodhpur. The results of this analysis are presented in Chapter 4. The report ends with a chapter on the technical areas that would help reduce the cost of solar ORC systems.

Chapter 2 - Solar ORC System Description

Before we start modelling an ORC system, we must understand the working as well as the limitations of the various subsystems involved. Figure 2 presents a schematic diagram of a typical solar ORC system (Patil, 2017). It comprises a solar field, which houses a series of solar radiation collectors and harnessing systems; a thermal energy storage (TES) system for storing and supplying thermal energy; and a power block (PB) based on Organic Rankine Cycle (ORC), which converts thermal energy into electrical energy. The subsequent sections contain a brief explanation of each of these major subsystems.

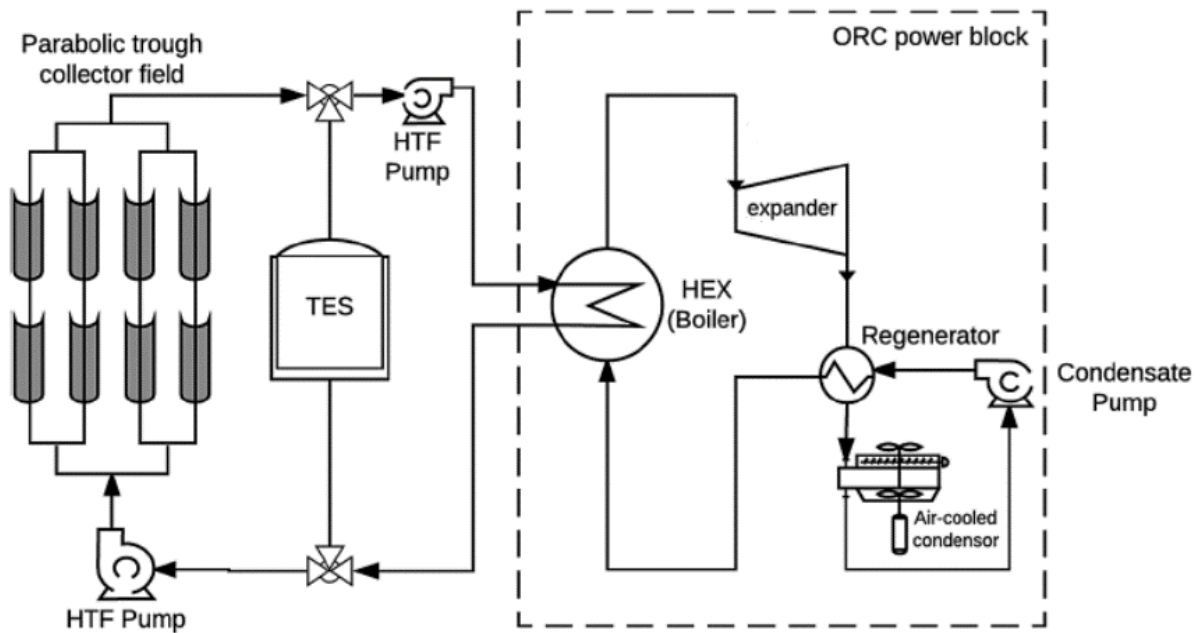


Figure 2. ORC power schematic showing solar field, TES and power block

2.1 Solar Field

The conversion of Sun's energy into thermal energy occurs in the solar field. To initiate this conversion, a series of reflectors concentrate solar radiation onto a receiver. The receiver converts the incident radiation into heat (or thermal energy), which is transported by a heat-transfer fluid (HTF) flowing through the receiver. The reflector and the receiver are together called the collector.

Collectors are the main components of a solar field; they account for nearly 40% of its overall cost. Parabolic trough collector (PTC), linear Fresnel reflector (LFR) and solar tower (ST) are some of the most widely used collectors. Among these types, PTCs are the most mature and preferred technology. It contains highly reflective parabolic mirrors made of glass or anodised aluminium of a parabolic shape. These mirrors have support frames to keep them stable and rigid (Ramaswamy et al., 2012). The axes of these collectors are aligned in the north-south direction; the mirrors can be tilted about the axes so that they can track the Sun from east to west. The width of these mirrors generally varies from as low as 1 metre to as high as 9 metres.

The parabolic reflectors focus the Sun's rays onto a cylindrical metal tube called the receiver. This metal tube is coated with a special selective substance (such as cermet, chrome and zinc black) which has a high radiation-absorbing ability in the solar spectrum. To protect this coating and reduce heat losses from the receiver, the metal receiver tube is enclosed within a glass tube. Vacuum is maintained

in the space between the glass tube and the metal receiver tube to further reduce heat losses. The diameter of the receiver tube (which is usually made of stainless steel) falls in the range of 25 mm to 90 mm.

The HTF transports the thermal energy to a thermal energy storage (TES) system, where it is stored and subsequently dispatched to the ORC PB. The HTF is usually water, synthetic/mineral oil or a eutectic molten salts mixture (potassium and sodium nitrate salts). Glycerol, Therminol VP, Therminol 55, monoethylene glycol (MEG) and propylene glycol are some popular, commercially available HTFs (Orosz 2009, Patil 2017, Ramaswamy 2012 & Quoilin S. 2013). The type of HTF used depends on the operating temperature of the solar field. For example, if the minimum and maximum temperatures in the solar field lie between 300°C and 530°C, then the preferred choice would be a molten salt mixture. ORC systems generally operate within a maximum of 200°C (low-temperature systems), where the preferred HTFs are glycol-based (such as MEG and propylene glycol) (Quoilin S. 2013 & Dai 2009).

2.2 Thermal Energy Storage (TES)

The primary task of TES is to supply thermal energy to the PB when sufficient thermal energy is not received from the solar field. TES ensures that the PB operates at design conditions as far as possible (for maximum utilisation of PB). TES also can supply thermal energy during intermittencies or fluctuations in the solar radiation. The number of hours of the thermal storage system is the key parameter which decides the size and the cost of TES. For compact-sized and low-cost storage systems, a material with a high thermal storage capacity will be preferred. The stability of the storage material at high temperatures is yet another crucial parameter. Thus, the choice of the TES material is based not only on cost and size, but also on the operating temperature range. The literature survey shows that sensible heat (heat stored in the material body)-based storage materials have the lowest cost (compared with latent or chemical heat based materials). Table 2 shows various solid-state type sensible heat storage materials (Tian, 2013). Reinforced concrete and NaCl are the preferred storage materials for solar ORC systems as they have the lowest cost per kWh.

Table 2. Solid state based sensible heat storage materials

Storage Materials	Working Temperature	Density	Thermal Conductivity	Specific Heat	Volumetric Specific Heat	Cost	
						(°C)	(kg/m ³)
Sand-rock minerals	200–300	1700	1.0	1.30	0.61	0.15	4.2
Reinforced concrete	200–400	2200	1.5	0.85	0.52	0.05	1.0
Cast iron	200–400	7200	37.0	0.56	1.12	1.00	32.0
Sodium Chloride	200–500	2160	7.0	0.85	0.51	0.15	1.5
Cast steel	200–700	7800	40.0	0.60	1.30	5.00	60.0
Silica fire bricks	200–700	1820	1.5	1.00	0.51	1.00	7.0
Magnesia fire bricks	200–1200	3000	5.0	1.15	0.96	2.00	6.0

2.3 Power Block

The PB is a major component in a power plant. PB includes boiler, an expander, a working fluid, a regenerator and a condenser (see Figure 2). The expander and the working fluid are the two most important components of a PB and significantly influence its overall efficiency. The following subsections discuss PBs in detail.

2.3.1 Expander

The expander is the heart of a PB where the conversion from thermal to electrical energy takes place. The conversion occurs when the high-pressure, high-temperature working fluid (in a vapour state) expands in the expander, resulting in the generation of electricity.

ORC expanders can be categorised into velocity type (such as axial turbines) and volume type (such as screw expanders and scroll expanders) (Quoilin T., 2013). ORC expanders differ quite significantly from steam turbines or expanders. ORC expanders have a greater expansion ratio and are much smaller (or compact) in size. The small size makes their design and manufacture highly challenging.

Turbomachines or turbines, screw expanders and scroll expanders are the three most popular types of expanders used in ORC systems. Screw and scroll expanders are of a positive-displacement (volumetric) type, whereas turbines are of a non-positive displacement type. The choice of technology depends on two key parameters: operating conditions and size of the ORC system (Quoilin T., 2013). According to Quoilin T. et al. (2012), the choice of expander depends also on the thermal energy source. Figure 3 shows the recommended choice of expanders for different capacities based on the thermal energy source (Quoilin T., 2012). In the case of solar, we can see that for capacities within 10 kW, scroll expanders are preferred; for capacities between 10 kW and 700 kW, screw expander or turbines are preferred; and for capacities above 750 kW, turbines are preferred.

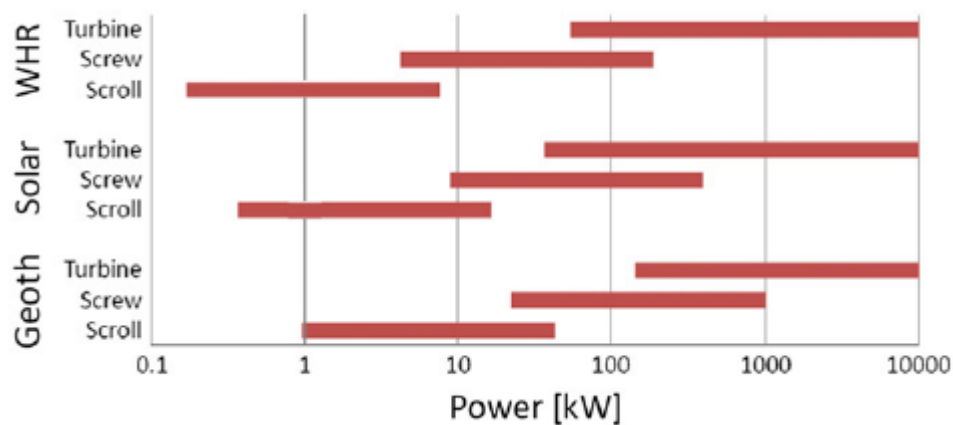


Figure 3. Optimal expanders for different capacities and for three thermal energy sources

A distinct advantage of using turbines over positive displacement expanders is that fewer stages are required when using turbines. For example, a single-stage turbine is adequate for medium- or low-temperature ORC systems. Another advantage is that under part-load conditions, turbines (radial inflow type) have a better efficiency. Because their rotation speed increases drastically with decreasing turbine capacity, turbines are not viable for small-scale applications. This is one of the major reasons why micro-scale turbines are still not available in the market.

Positive-displacement expanders (such as screw and scroll expanders) are a good replacement for turbines at low capacities as their rotating speed is limited. The other advantages they have over turbines are a higher reliability, good isentropic efficiency and the ability to tolerate the liquid phase during the expansion process. On the other hand, their major drawback is the need for lubrication. Because of the lubricants in the system, an oil separator is required at the expander exhaust. Using an oil-free expander could be a possible solution, but such an expander has leakage issues because of a higher tolerance. The other problems associated with positive-displacement expanders are poor efficiency at higher expansion ratios, a low built-in volume ratio and a low swept volume (Bao, 2013).

2.3.2 Working Fluid

The role of working fluid in an ORC system is to transport thermal energy and facilitate the conversion of thermal to mechanical energy. The conversion occurs in the expander where the working fluid undergoes phase change. In an ORC system, the choice of working fluid depends on the type of expander used. Choosing a single working fluid for all types of expanders would result in inefficient ORC operation.

ORC systems commonly use two types of working fluids: pure and mixed type. Some of the pure types are linear, branched and aromatic hydrocarbons, perfluorocarbons, siloxanes, ethers and alcohols. Because various ORC systems operate under different heat sources and working conditions, a single pure-type working fluid cannot be optimal for all ORC systems. Lakew et al. (2010) discovered that the R245fa working fluid would give a higher work output at temperatures higher than 160°C. However, if thermal and exergy efficiencies are considered paramount, Zhang et al. recommend the use of R123, R600, R245fa, R245ca and R600a as working fluids. Table 3 shows the recommended pure-type working fluids and their performance indicators for solar as the thermal energy source. The performance indicator is the primary parameter considered for selection of working fluid. These fluids can operate for heat source temperatures between 60°C and 200°C (Bao, 2013).

Table 3. Recommended pure type working fluids for solar as thermal energy source

Fluid	Performance Indicator	Ozone Depletion Potential (ODP)	Global Warming Potential (GWP)
R134a	Second Law Efficiency	0	1430
R245fa	Net Work Output	0	950
SOLKATHERM	First Law Efficiency	0	462
R227ea for 80–160°C and R245fa for 160–200°C	First Law Efficiency/Exergy Efficiency	0 (R227ea)	3220 (R227ea)
Hexane	First/Second Law Efficiency	0	129

Bao (2013) suggest that one should consider not only thermodynamic performance and system economy but also other factors such as system pressure, expander or turbine design, maximum and minimum bearable temperature and environmental and safety considerations while selecting a working fluid. Researchers also consider the temperature of the heat source when deciding on the optimal pure-type working fluid. Figure 4 shows the optimal pure-type working fluids for different source temperatures (Wang, 2013).

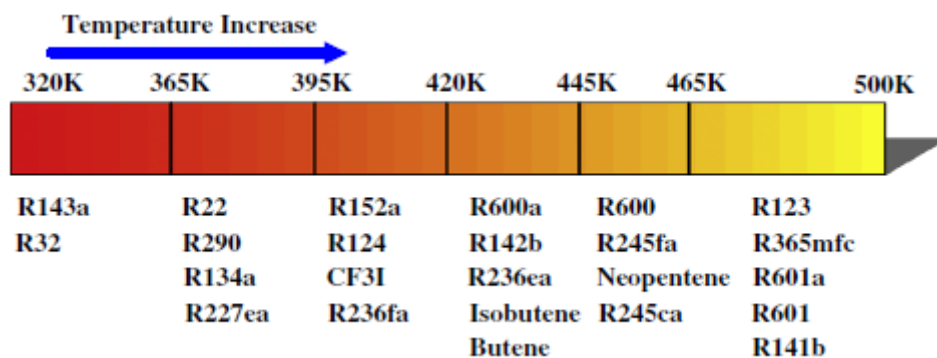


Figure 4. Optimal working fluids based on heat source temperature

Variations in heat source temperature can result in poor cycle performance. This is because pure working fluids have a constant boiling and condensing temperature. However, the performance can be improved using a mixture of organic fluids, such as R245fa–isopentane, R22 70%–R114 30% and isobutane–isopentane. As ORC systems using a mixed-type working fluid can operate under varying source temperatures, the exergy (second law) efficiency is generally high. Unfortunately, it is quite arduous to prepare an optimum composition as these mixtures have complicated mixing rules (Bao, 2013).

2.3.3 Heat Exchangers (HEX) / Condensers

HEX and condensers are the components where thermal energy transfer occurs from the heat source or to a heat sink respectively. The thermal energy transfer occurs to and from the working fluid flowing through these components. The two most common types of HEX are the shell-tube type and the plate-type. Large-scale systems use the shell-tube type, while small-scale systems (which require a compact design) use the plate type. HEXs are generally rugged in nature, as they are designed to withstand high corrosion and high temperatures (Quoilin T., 2013).

Heat recovery in a HEX is by two means:

- By direct exchange of heat between the thermal energy source and the working fluid
- Through an intermediate HTF loop, which transfers heat from the waste heat source to the evaporator

The direct-transfer type is simpler and more efficient but has numerous issues (Quoilin T., 2013). As a result, most commercial ORC systems use an intermediate HTF loop type HEX (Quoilin T., 2013). The optimisation of HEX is based on two key parameters: pressure drop and efficiency. This optimisation should be prudently done as the HEX cost accounts for a bulk of the power block cost.

3.2 Engineering/Technical Model

The model aims to calculate the thermal energy supplied by the solar field and allocate the energy to various subsystems of the ORC system (TES and power block). It begins with the reference area calculation and moves on to energy budgeting. Figure 6 presents a flow chart showing the sequence of events in the techno-economic model. The subsequent sections describe in detail the steps involved in the technical model.

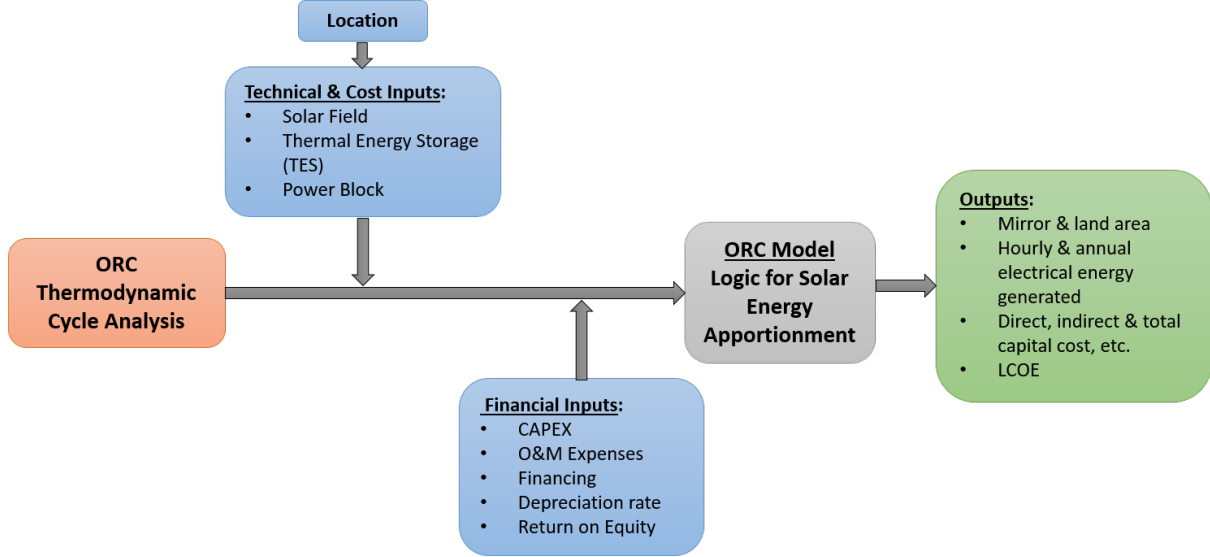


Figure 6. Flow-chart of solar ORC techno-economic model

3.2.1 Reference Mirror Area Calculations

The first set of calculations in the technical model involves the calculation of the reference mirror area (A_r). This reference area refers to the area required to run the power block at its gross rated or design capacity. It is calculated for the maximum solar power incident on the mirrors, which is $(DNI \times \cos\theta)_{max}$. DNI is the direct normal irradiance which is the component of solar radiation which is normal to earth's surface. $\cos\theta$ is the Cosine component of the angle between the normal to the mirror and the Sun's ray. The steps involved in the calculation (which was performed on MATLAB) are as follows:

1. For the given location, the $(DNI \times \cos\theta)_{max}$ is calculated using values from the hourly DNI database
2. The total capacity of the ORC power block is read from user input and assigned as $P_{t,cap}$
3. The thermal power supply required for the power block to operate at design capacity is calculated and assigned as $P_{th,d}$. The value is based on the efficiency of the power block (η_{pb})
4. The thermal power to be supplied to the HTF is calculated by considering the HEX efficiency (η_{HEX}) and is assigned as $P_{htf,d}$
5. The absorber tube efficiency ($\eta_{abs,d}$) is calculated using our in-house code. This efficiency is based on the $(DNI \times \cos\theta)_{max}$ value
6. Now, using the $P_{htf,d}$ and ($\eta_{abs,d}$) values, the solar power required to impinge on the absorber tube is calculated and assigned as ($P_{abs,d}$)
7. The reference mirror area (A_r) is calculated using ($P_{abs,d}$) and $(DNI \times \cos\theta)_{max}$.

3.2.2 Solar Multiple

The solar field that was designed based on the reference area will receive maximum solar radiation $(DNI \times \cos\theta)_{max}$ for only a brief time during a year. As a result, the power block will operate at sub-design conditions for most of the year. This will result in plant operations becoming economically unviable. To offset this, the reference area for a solar field has to be multiplied by a factor. Solar multiple (SM) is the product of the multiplication factor and the reference area A_r . $SM=1$ indicates that A_a will be equal to A_r . For optimal usage of the PB, the SM must be greater than 1. However, a very large value of SM would increase the capital cost of the ORC plant. Therefore, an optimal SM has to be determined, which would be a trade-off between the energy generation and the capital cost. The process of determining the optimal SM is explained in the following sections.

3.2.3 Details of the Engineering Model

After obtaining the reference area for the given ORC system, the next step is to calculate the solar energy collected and utilised for generating electrical energy. We have developed an engineering model to perform energy apportionment of the solar thermal energy. Before describing the model, let us look at the technical inputs required:

- Capacity in kW
- Reference mirror area (A_r) in m^2
- Solar multiple (SM)
- Hourly DNI data
- TES capacity
- Solar field efficiency (η_{SF})
- TES efficiency (η_{TES})
- HEX efficiency (η_{HEX})
- ORC power block efficiency (η_{ORC})
- Power block minimum part load
- Working fluid properties

The basis of the model is the CSTEP's Techno-Economic Model (CSTEM) CSP tool, while MATLAB is the coding platform. Here is a brief description of the logic followed for energy apportionment/budgeting in this model:

1. The values under technical inputs are read and assigned appropriate variables. The hourly DNI data for the given location is usually stored in an Excel file, which is read as an array in MATLAB.
2. The thermal energy required for running the power block (PB) at its design load ($Q_{PB,des}$) is calculated.
3. For any i^{th} hour (i taking values from 1 to 8760), the thermal energy delivered from the solar field ($Q_{SF,i}$) is calculated using the DNI data, actual mirror area and solar field efficiency.
4. The value of $Q_{SF,i}$ is checked to determine whether it is greater than, equal to or less than $Q_{PB,des}$
5. If $Q_{SF,i}$ exceeds $Q_{PB,des}$, the following logic is executed:
 - a. The power block is operated at its design capacity, and the surplus energy from the solar field is calculated and sent to the TES for charging.
 - b. If the TES is not fully charged, this surplus energy is used for charging it. If some energy remains unutilised even after the TES has been fully charged, the mirrors have to be defocused or the surplus energy has to be suitably dumped into the environment.
 - c. If the TES is already fully charged, this surplus energy indicates that the mirrors have to be defocused or the surplus energy has to be suitably dumped into the environment.
6. If $Q_{SF,i}$ is equal to $Q_{PB,des}$, the PB is run at design load and the TES is neither charged nor discharged.
7. If $Q_{SF,i}$ is less than $Q_{PB,des}$, the following logic is executed:

- a. $Q_{SF,i}$ is checked to determine whether it exceeds the minimum part load for the PB ($P_{PB,min}$). If it does not exceed this load, the energy generated from the PB is assigned as zero. $Q_{SF,i}$ is then sent to the TES for charging (if the TES is not already fully charged).
- b. If $Q_{SF,i}$ is equal to or exceeds $P_{PB,min}$, the deficit energy is calculated. The TES is checked to determine whether it can supply this deficit energy. If it can supply the deficient energy, the required energy is drawn from it and the PB is run at design load. Appropriate changes are made in the TES to compensate for the energy supplied.
- c. If the TES cannot supply the deficit energy, all of the energy in storage is drawn and the PB is operated at part-load conditions. The energy stored in the TES is set to zero.

Executing the sets of logic described in these steps for all 8,760 hours in a year results in the annual electrical energy generated by the ORC system. The

3.3 Financial Model

We ran the financial model after the completion of the engineering model. This model requires the calculation of financial parameters such as direct and indirect capital costs as well as operations and maintenance costs. The model uses these costs along with technical outputs and other financial parameters to calculate the levelised cost of electricity (LCOE). A brief overview of some important financial parameters along with the outputs from the engineering model is provided here. One can refer to Ramaswamy et al. (2012) for a more detailed description and the formulas used for calculating the parameters.

3.3.1 Technical Outputs for the Financial Model

Some of these outputs (in italics) from the engineering model are given below, and they serve as the inputs to the financial model. The calculations for these parameters are given in Annexure. The non-italicised parameters are direct inputs provided by the user and the others are calculated metrics by the model.

- Capacity of the power block (*PB*)
- Power rating of all subcomponents of the ORC system
- Chord width of parabolic mirrors (*C*)
- Length of receiver tubes
- *Actual mirror area (A_a)*
- TES capacity (*t_s*)
- *The maximum amount of thermal energy that can be stored in the TES system ($E_{tes,max}$)*
- The volume of HTF and working fluid
- Number of swivel joints and hydraulic drives
- *Annual gross electrical energy generated*
- *Capacity Utilization factor (CUF)*

3.3.2 Financial Parameters

The following financial parameters are calculated using the technical outputs mentioned above. Ramaswamy et al. (2012) lists the formulae that we used for calculating the parameters.

3.3.2.1 Capital Costs

They consist of two parts: direct and indirect capital cost, which are described below.

- i. Direct Capital Cost (DCC) – The sum of the following costs will result in the DCC:
 - Mirrors and support structure costs

- Land cost
 - HTF and TES costs
 - ORC PB subcomponents cost (includes expander and working fluid)
- ii. Indirect Capital Cost (ICC) – This cost is the sum of engineering procurement cost (EPC), project management cost (PMC), interest during construction (IDC) and pre-ops expenses. EPC, PMC and IDC are taken as a percentage (usually 5%) of DCC.

3.3.2.2 Operations and Maintenance (O&M) Costs

The operations cost comprises the salaries paid to support staff and engineers, plant water cost and insurance cost. On the other hand, the maintenance cost involves the upkeep of various subcomponents of the ORC plant, such as washing the mirrors, maintaining the support structures, refilling the HTF and working fluids and cleaning and greasing the expanders.

3.3.3 Levelised Cost of Electricity (LCOE)

The price at which a unit of electricity (kWh_e) is sold to customers represents the LCOE. This is an important output from the model as it decides the feasibility of the ORC plant. LCOE calculations are in accordance with the guidelines described by the Central Electricity Regulatory Commission (CERC). LCOE is defined as the ratio of the net present value (NPV) of the incurred project expenses (PE) for the lifetime of the plant in INR, which is represented as NPV (PE), to the NPV of the total electrical energy supplied to the grid over the plant's lifetime, NPV (E_{grid})¹.

$$LCOE = \frac{NPV (PE)}{NPV (E_{grid})/1000}$$

where LCOE is in ₹/kWh.

NPV (PE) is obtained as follows:

$$NPV (PE) = \sum_{i=1}^{PL} \frac{PE(i)}{\left(1 + \frac{Discount\ rate}{100}\right)^i}$$

The project expenses (PE) for the i^{th} year are calculated as follows:

$$PE(i) = Total\ O\&M\ (i) + Depreciation\ (i) + Interest\ on\ loan\ term\ (i) \\ + Interest\ on\ working\ capital\ (i) + Return\ on\ equity\ (i)$$

3.3.4 Details of the Financial Model

The steps involved in calculating the LCOE (as prescribed by CERC) are described in Ramaswamy et al. (2012). Some minor modifications were made to the model described in Ramaswamy et al. (2012) to make it compatible with solar thermal systems. Some of these modifications are as follows:

- The cost of the components, such as PTCs, thermal storage, HTF and pump that are unique to solar thermal systems were included in the capital cost calculations.
- Changes to the maintenance cost were made as PTCs require regular cleaning.
- We assumed that for the entire lifetime of the plant, the annual electrical energy production is constant.

¹ E_{grid} : Annual electrical energy supplied to the grid. This excludes the auxiliary energy consumed by the system. $E_{grid} = E_{grid,t} - E_{Aux}$

Chapter 4 - Techno-Economic Assessment

In this section, we will use the technical and financial models discussed previously to perform a case study. The location chosen is Jodhpur as it receives the highest solar energy in India. We will present the technical parameters such as annual electrical energy and solar-to-electric efficiency for various solar multiples (SMs) and TES systems. Also, important financial parameters, such as LCOE and capital costs, will be presented for various SMs and TES systems.

4.1 Technical Inputs

Based on our discussions with IISc and Thermax (industrial partner in SERIUS) and from the literature survey, we used various technical inputs for our model. Table 4 presents a list of these inputs. We chose a scroll-type expander for our analysis because IISc & MIT are jointly working on the design and development of such an expander.

Table 4. Technical inputs for an ORC system located in Jodhpur

Parameters	Value/Type
Solar field collector efficiency ($\eta_{sol,col}$)	70%
HTF	Glycerol
TES (η_{TES}) and HEX (η_{HEX}) efficiencies	$\eta_{TES} = 97\%$ & $\eta_{HEX} = 95\%$
Power block capacity	100 kW
Power block - cycle efficiency (η_{PB})	10.7%
Auxiliary power consumption	5% of the power generated (optimistic)
Working fluid	R245fa
Minimum cut-off load of power block	70% of the rated design capacity of power block

We carried out solar field efficiency calculations using the in-house code for a maximum operating temperature of 200°C. The literature survey provided the HEX and TES efficiencies. As CSTEP and IISc were interested in off-grid applications of ORC systems, we decided to go with a 100kW system. A 100 kW system could power a small community centre (such as a hospital) or around 50 small houses in a village. We chose the power block efficiency from Patil et al. (2017) for a maximum operating temperature of 150°C. The rationale for choosing R245fa as the working fluid was that it would allow the ORC system to operate efficiently in moderate temperatures.

4.2 Financial Inputs

We obtained the necessary financial inputs from the literature survey and from our industrial partner Thermax. Table 5 presents the inputs we considered for the model.

Table 5. Financial inputs for an ORC system located in Jodhpur

Parameters	Value/Type
Solar field cost	INR 10,000/m ²
Land cost	INR 208/m ²

Thermal Energy Storage (TES) cost	INR 67/kWh
Power block cost	INR 63,000/kW _e
Indirect costs	5 % of direct costs

We estimated the cost for the solar field considering Thermax’s commercially available solar field components. We further verified the solar field costs by analysing the cost of products supplied by other original equipment manufacturers (OEMs). We selected the TES material based on the lowest cost per kWh_t. Concrete-based TES material turned out to be the most economical among the available options (refer Table 2). The PB cost includes the costs of the expander, working fluid, boiler and condenser. The plant life consider for this analysis is 25 years of operation.

4.3 Results

4.3.1 Engineering Assessment

4.3.1.1 Effect of Solar Multiple (SM)

Figure 7 shows the variations in the electrical energy generated annually with increasing SM for various TES capacities (or hours). The increase in annual electrical energy generation with SM is because of the increase in energy coming from the solar field. The increase in annual electrical energy is sharp initially and plateaus as we move towards higher SMs. This is because at lower SMs, the energy supplied from the solar field is not sufficient to run the plant at design capacity. As the SM increases, the plant tends to move towards full design capacity, resulting in the sharp rise in Figure 7. After a certain SM, the jump in annual electrical energy generation is not as drastic because the solar field would be generating surplus thermal energy.

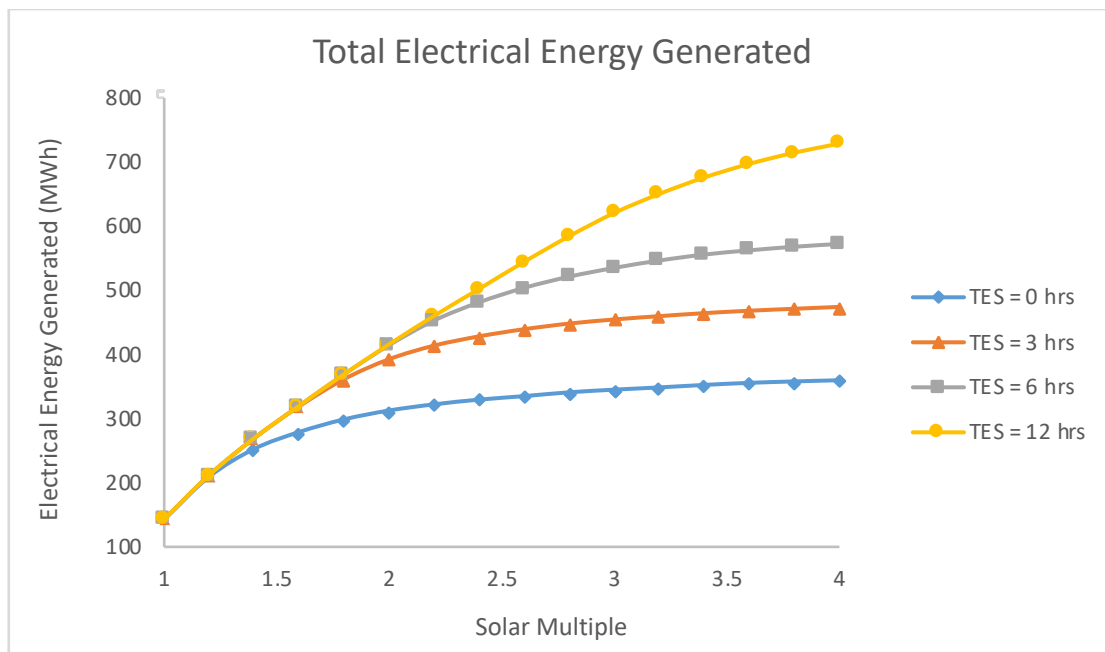


Figure 7. Variations in annual electrical energy generated with solar multiple for various TES

4.3.1.2 Solar-to-Electrical Conversion Efficiency

Figure 8 shows the annual efficiency variations with SM for various TES systems. The annual efficiency is the ratio of the total annual electrical energy generated to the annual solar energy impinging on the solar field. It is expressed as (Ramaswamy et al., 2012),

$$\text{Annual efficiency} = \frac{\text{Total annual electrical energy generated}}{\text{Annual solar energy impinging}}$$

$$\text{Impinging annual solar energy} = A_r \times SM \times (\Sigma DNI \times \cos\theta)$$

Figure 8 indicates the optimal SM for each TES system considered. The maximum efficiency for TES= 0 hrs occurs at 1.4 SM, for TES = 3 hrs at 1.8 SM, for TES =6 hrs at 2 SM and for TES = 12 hrs at 2.6 SM.

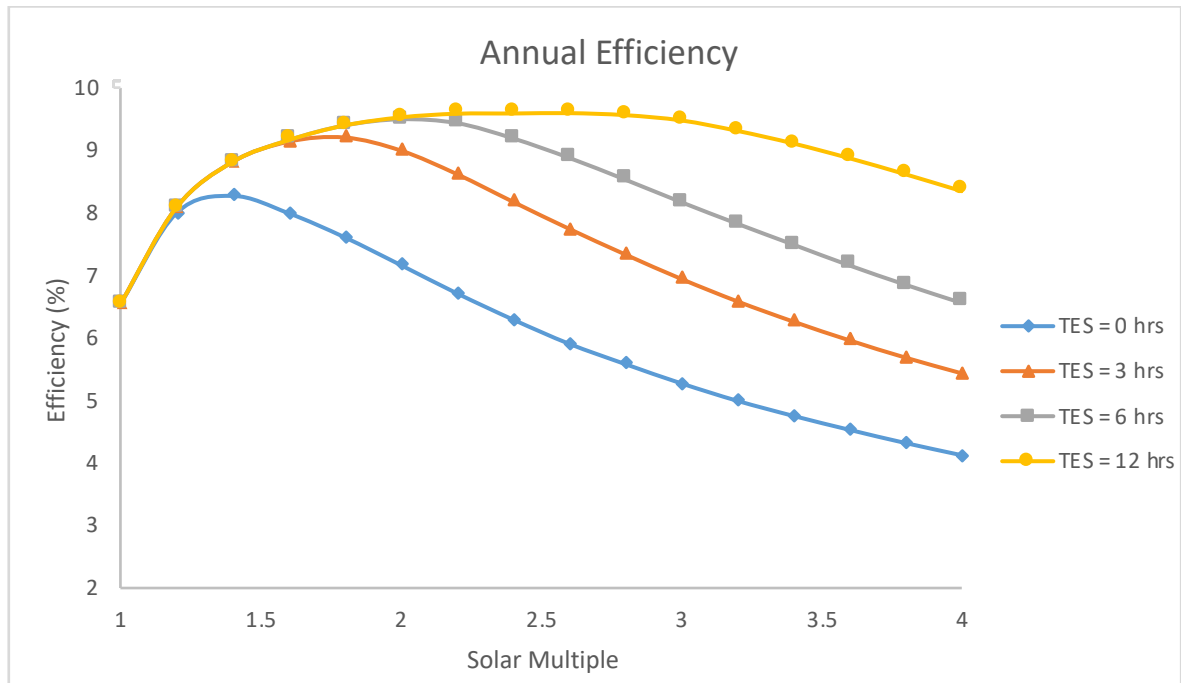


Figure 8. Variations in annual efficiency with solar multiple for various TES

4.3.2 Economic Assessment

4.3.2.1 Variations of LCOE & Capital Cost for Optimal SM

Figure 9 shows the variations in LCOE and capital cost with TES. As the figure shows, we have not considered 0 hrs of TES because the LCOE and capital cost would be very high and such an ORC system would be unviable. The trends in LCOE and capital cost are as expected, with the former decreasing and the latter increasing with TES. The decrease in LCOE is because of the increase in the capacity utilisation factor (CUF) (ranges from 47% to 77%) of the plant. As a result of this increase in CUF, more energy is available for sale with increasing TES. On the other hand, the capital cost increases because of the increase in the sizes of the solar field and the TES. On the whole, the LCOE is high compared to diesel generator or biomass plant.

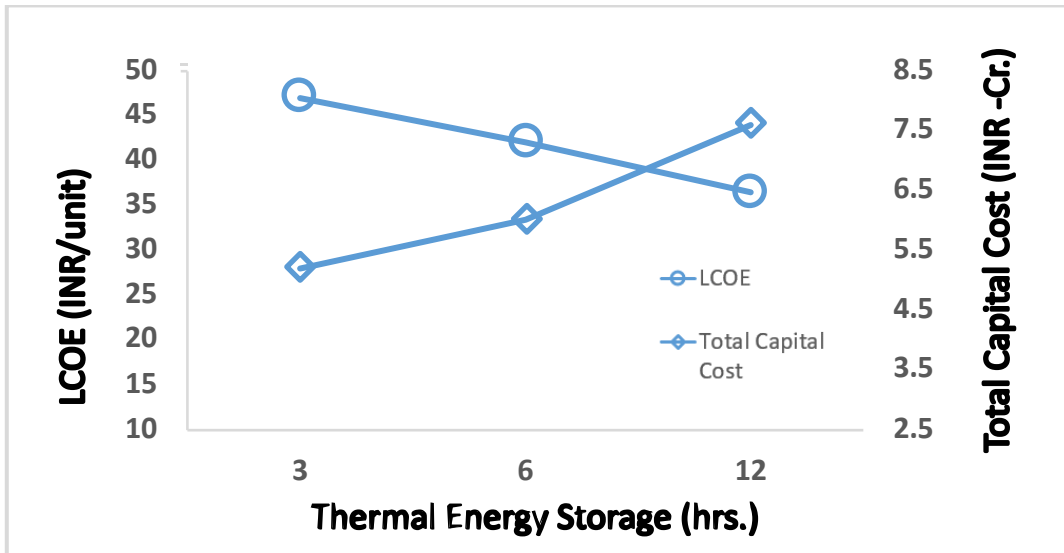


Figure 9. LCOE and capital cost variations with TES for optimal Solar Multiples

4.3.2.2 Capital Cost Break-Up for a Single Case

Figure 10 provides a break-up of capital cost when TES is 6 hours. This pie chart helps us weigh the relative contributions of the ORC components towards the total capital cost. It is evident from the chart that the maximum contribution is from solar field components, followed by the indirect capital cost and the power block. Thus, for ORC systems to become cost-competitive, costs associated with solar field components and the PB have to drop considerably.

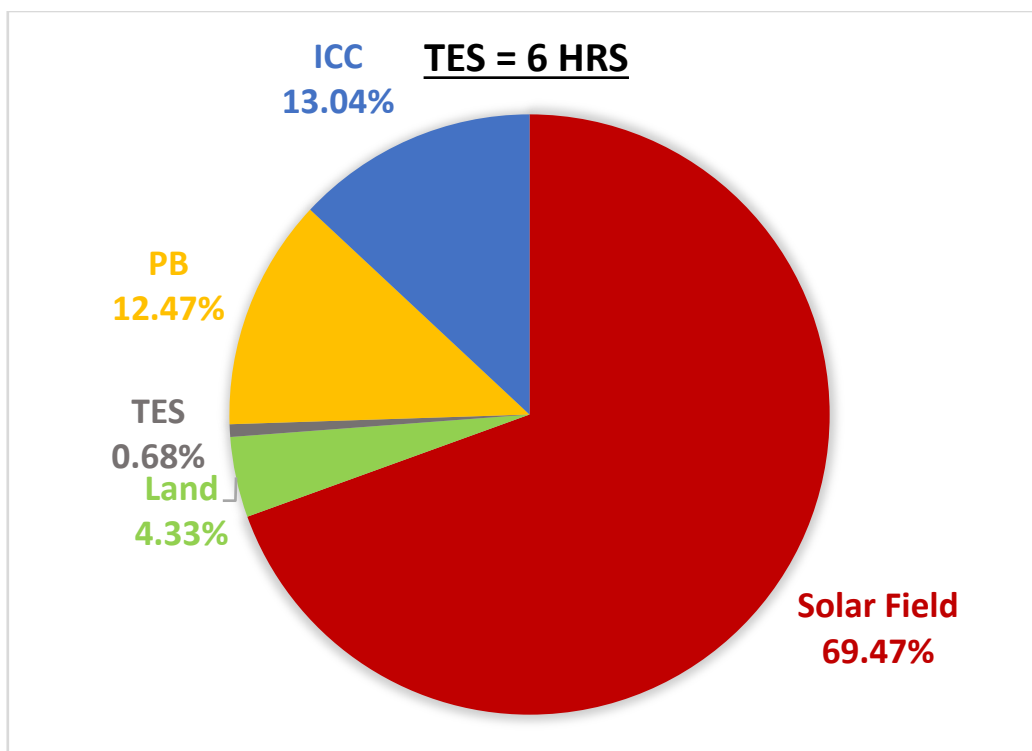


Figure 10. Capital cost break-up for TES of 6 hours

4.4 Cost Reduction Potential

Manufacturing components such as the PTC receiver tube and the ORC expander locally rather than importing them could help decrease the total capital cost. This might also result in a reduction of the LCOE. Improving the efficiency of the ORC expander will further reduce the LCOE.

We performed a sensitivity analysis for a plant life of 25 years to understand the effects of local manufacturing and increase in the expander efficiency on LCOE and capital cost. Figure 11 presents the results of this analysis.

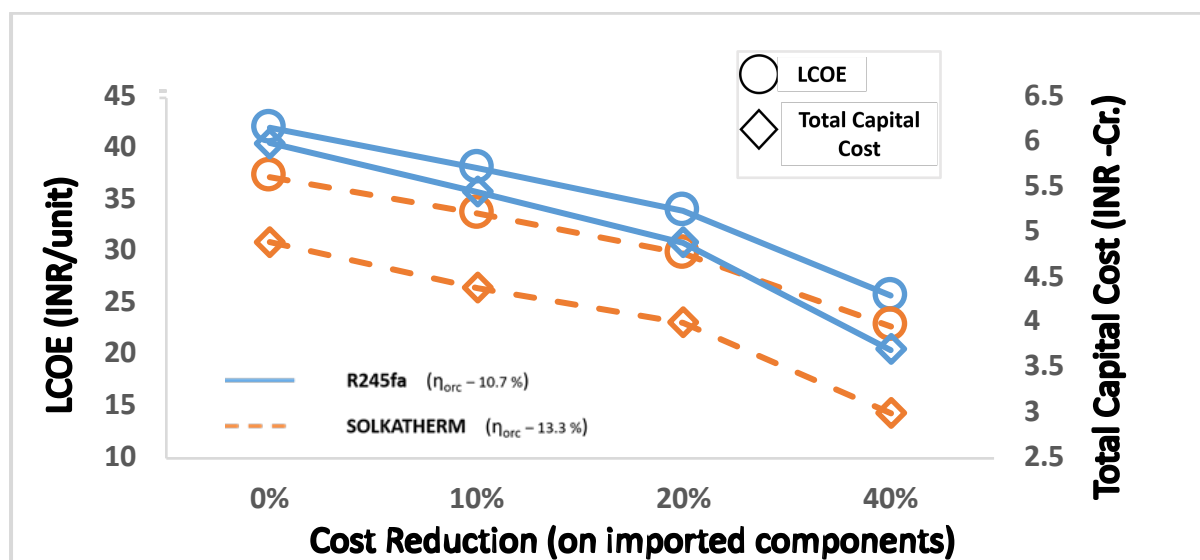


Figure 11. Variations in LCOE and total capital cost with cost reduction and ORC efficiency

We conducted this simulation for a system with 6 hours of TES. To achieve an efficiency of 13.3%, the maximum operating temperature for the ORC cycle had to be high. We considered an operating temperature of 200°C to achieve this efficiency and chose SOLKATHERM as the working fluid. We observed that the ORC system may become viable if the cost of imported components reduces by 40% and the efficiency increases to over 13%.

In the case presented above, the auxiliary power was assumed to be an optimistic 5%. Under current realistic scenario, the auxiliary power would be much higher than 5%. In order to capture the variations of LCOE with auxiliary power, we repeated methodology (mentioned in previous sections) for auxiliary power variations of 10%, 15% and 20%. Figure 12 shows the results of the simulation. We observe that the LCOE increase with the auxiliary power for any given TES. This shows that reducing the auxiliary power could also be an area of research focus.

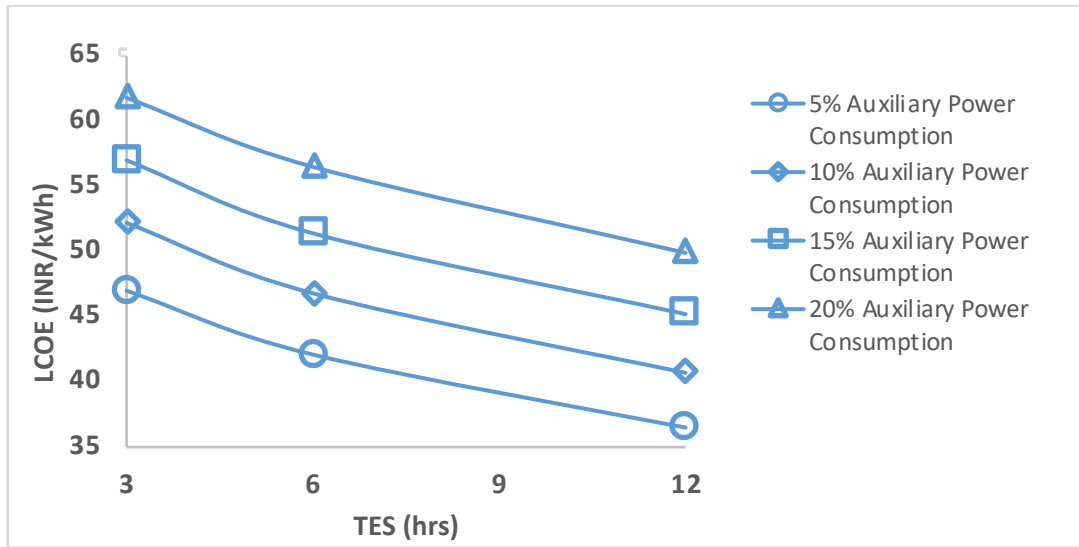


Figure 12. Variation of LCOE with TES for various auxiliary power consumption

Chapter 5 - Conclusion

A techno-economic analysis of a low-cost ORC configuration revealed that its capital cost and LCOE are relatively high compared with an equivalent off-grid PV plant. These results contradict the findings of Orosz et al. (2009) and the deviations could be because of differing location and cost of solar and ORC components. None the less, from the point of view of investors, an ORC plant would be uneconomical to setup in India and they would rather opt for a PV plant.

The sensitivity analysis indicated that the ORC plant can be made economically viable by reducing the cost of some key solar-ORC components and increasing the efficiency of the subsystems (to reduce auxiliary power). Costs can be reduced via R&D and locally manufacturing some of the imported components. Setting up manufacturing facilities in India will not be too challenging, as we already have some of the necessary technology available locally. Also, a tie-up with foreign manufacturers based in Germany and Spain could bring about a technology transfer of key components. In the long run, the R&D route would be more beneficial as it would facilitate technological development for local use. However, for the short-term, technology transfer would be the ideal solution.

Another way to reduce cost would be to improve the operating efficiency of the ORC plant. Improving the expander design and increasing the operating temperature to more than 200°C can help bring about a higher efficiency. Unfortunately, increasing the operating temperature would require an expensive PTC system, which would increase the LCOE and capital cost sharply. So, the only viable option would be to improve the design of the ORC expander so as to improve its cycle efficiency.

Annexure

A.1 Actual Mirror Area

$$A_a = SM \times A_r$$

where,

A_a → Actual mirror area of PTCs (m²)

A_r → Reference mirror area of PTCs (m²)

SM → Solar Multiple

A.2 Maximum TES stored

$$E_{tes,max} = \frac{(Capacity \times t_s)}{\eta_{tes}}$$

where,

$E_{tes,max}$ → Max. energy stored in TES (kWh_t)

$Capacity$ → Design capacity of power block (kW_e)

t_s → Capacity of TES (hrs)

η_{tes} → Efficiency of TES

A.3 Gross Annual Electrical Energy Generated

$$E_{grid,t} = \sum_{i=1}^{8760} (expander\ work)_i$$

where,

$E_{grid,t}$ → Gross annual electrical energy generated by expander (kWh_e)

i → an hour in 8760 hours

A.4 Capacity Utilization Factor (CUF)

$$CUF = \frac{E_{grid}}{Capacity \times 8760}$$

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