TECHNO-ECONOMIC ASSESSMENT AND THERMODYNAMIC STUDIES ON SOLAR THERMAL POWER GENERATION

By

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DOCTOR OF PHILOSOPHY

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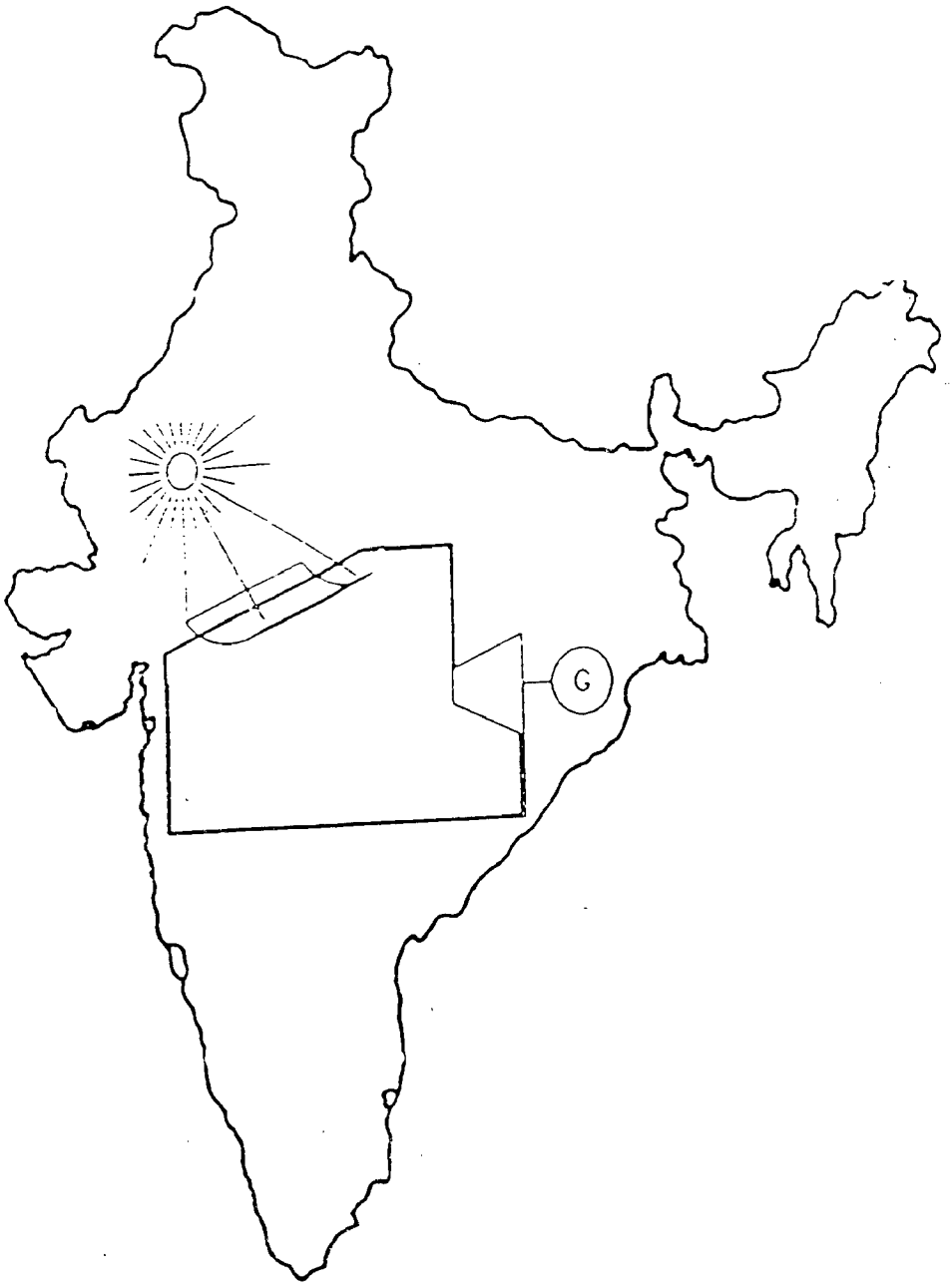
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'THE QUESTION THAT COMES UP AMONG POLICY MAKERS, AGAIN AND AGAIN IS : IF NOT COAL, AND IF NOT NUCLEAR, THEN WHAT ?

CHRISTOPHER FLAVIN
STATE OF THE WORLD

'A CENTRAL ASPECT OF THE CURRENT CULTURAL TRANSFORMATION IS THE SHIFT FROM THE PETROLEUM AGE AND THE INDUSTRIAL ERA TO SOLAR AGE'

HAZEL HENDERSON
THE POLITICS OF THE SOLAR AGE : ALTERNATIVES TO ECONOMICS

CERTIFICATE

This is to certify that the thesis entitled "*TECHNO -ECONOMIC ASSESSMENT AND THERMODYNAMIC STUDIES ON SOLAR THERMAL POWER GENERATION*" being submitted by Mr. **NARENDRA SINGH** to the Indian Institute of Technology for the award of the degree of '**Doctor of Philosophy**' is a record of bonafide research work carried out by him under my guidance and supervision. The research material contained in this thesis has not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

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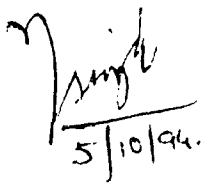
DECLARATION

I hereby declare that the present work in this thesis titled "*TECHNO -ECONOMIC ASSESSMENT AND THERMODYNAMIC STUDIES ON SOLAR THERMAL POWER GENERATION*" in fulfillment of the requirements for the award of the degree of Doctor of Philosophy and submitted in the Centre for Energy Studies is an authentic record of the research work carried out by me during the period from July, 1989 to October, 1994, under the supervision of Dr. S.C.Kaushik, Assistant Professor, C.E.S., I.I.T Delhi. The matter embodied in this thesis has not been submitted by me for the award of any other degree.



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The inspiration instilled by my wife, Dr.(Mrs.) Ritu Singh - my intellectual companion and life partner - to achieve higher heights of success in life have provided me the strength to complete the thesis. My little son Kunwar Nishant Singh's naughty, loving activities are beyond words as they reinvigorated my strength to complete this work.

SUMMARY

Solar thermal power generation is one of the most promising aspects of solar energy utilisation. The high thermodynamic quality of solar radiation has led researchers to explore the conversion of concentrated solar radiation into electricity by means of a thermodynamic cycle. Limitations of solar thermal conversion efficiency are visualised as reported in the literature. Peculiar considerations of solar thermal energy affect the choice of heat cycle and solar collection options for solar thermal power generation. The present thesis deals with assessment of solar collection technology for power generation options, thermodynamic considerations and analysis of solar power cycles and techno-economic assessment of solar thermal power generation in Indian context.

Conventional power plants are designed for maximum power output (which minimizes the capital cost of the plant) rather than maximum thermal efficiency which could save on fuel cost. However, for solar thermal power plants, capital cost is much more than the operation and maintenance cost, as the fuel is free, it is desirable to achieve maximum power in finite time rather than maximum work in infinite time. The author has intended to investigate the optimum operating temperatures for Carnot cycle at maximum power output. Finite time thermodynamic analysis based on non- equilibrium thermodynamics is carried out for the power cycles used for solar thermal power generation. Thermodynamic modelling and parametric studies for the potential power cycles- the Rankine and Brayton have been carried out and effect of component temperatures/ effectiveness on their thermal efficiency has been studied (using respective working fluids) and possible improvements

have been predicted for wide range of operating parameters. A case has also been established for Stirling engine's need and potential in India along with the constraints in the present conditions. A parametric study of its solar operation and thermodynamic feasibility has been presented.

Design conceptualisation of a 30 MW solar thermal power plant based on parabolic trough technology has been presented and life-cycle-cost-benefit analysis for both, Solar Alone and Solar Hybrid plant options have been carried out. It has been found that the Solar Hybrid system is a better alternative to solar alone system because the balance of the plant can be better utilised and per unit cost of generation becomes more favorable. Besides, the effects of other critical economic parameters on overall economic viability of the plant have been studied. Solar thermal power generation has faced significant technical, economic and policy barriers in the past. Its potential in the future will depend in large part on its ability to over come the barriers such as: Low energy prices; Lack of recognition for externalities; Uncertainties on expiry of tax-credits etc.

PREFACE

Energy crisis of the 1970s forced the world to realize that fossil fuel reserves are depleting rapidly and may be exhausted within the foreseeable future. Subsequently, some other factors such as environmental concerns, strategic dependence on imported oil, foreign exchange crunch led the Govts./policy planners/researchers to look for alternate power generation technologies including solar thermal power generation.

Significant progress has been made in the development of techno-economically viable solar thermal electric technologies in the last one and a half decade [Hall, 1984; Grasse, 1988; Alpert, 1991]. Support of certain policy initiatives (PURPA & Energy Tax Act, 1978) led to the establishment of 354 MW_e capacity of Solar Electric Generating Systems(SEGS) based on parabolic trough collectors in California, USA.

In India, these developments have generated a lot of interest in solar thermal power generation because of its large power deficit; location in sun belt; adequate manpower, infrastructural and organisational capabilities to adopt a new technology etc. It may be noted that in India, the demand for electricity always exceeded the supply. Considering the growth rates in power demand and availability of capital to build power generation capacity, this situation is most likely to exist during the time of a reasonable planning horizon. According to an

estimate of the Central Electricity Authority [Electric Power Survey 1985] deficit on produced energy for the year 1994-95 is projected as 2.9 GWh. Perhaps, realising the importance of solar power generation, the Govt. of India has also taken significant policy initiatives in the recent past, in regard to solar power generation - solar thermal as well as solar photovoltaics. Under the Build-Own-Operate scheme, the Govt. of India has offered several incentives to prospective entrepreneurs willing to set up MW scale solar thermal power plants. These include one time subsidy; 100% tax depreciation; wheeling, banking and buy-back facility for the generated electricity etc.

Two pilot scale experiments were taken up to demonstrate the techno-economic feasibility of solar thermal power generation in India [Murthy et al., 1987; Singh et al., 1990]. The author of the thesis was involved with the installation, commissioning and evaluation of the 50 kW solar thermal power plant at Solar Energy Centre, Gwal Pahari. The major demonstration plant-50 kW solar thermal power plant, is facing closure because of various problems such as breakage of collector mirrors, degradation of heat collection elements and lack of availability of spare parts etc. It may be noted that there are several research groups working on various facets of solar thermal energy utilisation in the country but there is lack of R&D activity in the field of solar thermal power generation. Therefore, the need & relevance of solar thermal power generation

and outcome of 50 kW solar thermal power plant prompted the author to take up research in the field of solar thermal power generation.

The R&D work in the solar thermal power generation can broadly be divided in the following categories : solar collection and thermal storage subsystems, thermodynamics of solar thermal power conversion; techno-economic studies; hardware design, development and pilot-scale demonstration plants etc.

The present thesis aims at `**Techno-economic Assessment and Thermodynamic Studies on Solar Thermal Power Generation**'.

Chapter-I, presents major technology developmental efforts and systems characteristics of the main demonstration plants representing the three prominent solar thermal power generation options. Each solar thermal power generation option is characterised by the shape of the mirrored surface on which sunlight is collected and concentrated - the parabolic trough based system, the central receiver system and the parabolic dish based system. The strength & weaknesses of the three options have also been assessed in this chapter.

Peculiar characteristics of solar energy affect the choice of the power conversion cycle. The commonly known cycles for solar thermal power conversion are the Rankine, Brayton and Stirling cycles. Basic thermodynamic considerations and thermal

efficiency aspects of these cycles have been presented in **Chapter-II**.

Chapter-III presents analysis of a solar thermal heat engines in terms of finite heat transfer rates and internally reversible heat engine. Curzon and Ahlborn, 1975 applied the discipline of finite time thermodynamics to the Carnot cycle for calculating the real Carnot engine efficiency at maximum power output. Tabor (1979) and Exell (1987) have discussed optimum operating temperature and efficiency for solar thermal power generating systems based on flat plate collectors. However, they have not taken into account the Curzon-Ahlborn efficiency and assumed only perfect reversible solar heat engines. Boehm (1986), Gordon (1989) and Singh and Kaushik (1994) have applied finite time thermodynamics to Carnot solar heat engines in order to find out optimum operating temperatures for solar thermal power systems. This analysis has been used to find out upper bound on efficiency for a wide range of operating temperatures characterising various solar thermal power systems. Finite time optimisation of the Rankine and Brayton heat engines has also been investigated by Lee (1991) and Wu (1990) respectively. A brief discussion of their finite time optimization has also been presented in this chapter.

The generation of electrical power from solar energy has not yet been shown to be economical for small scale systems. The problems associated with solar Rankine heat engine are many and

the major constraint arises from the fact that solar collection efficiency decreases while thermal efficiency of Rankine heat engine increases as the operating temperature increases. The efficiency limitation and the economic consideration of the combined solar collector and the Rankine system make this option suitable for large scale power generation only. The application of Freon and steam Rankine cycle heat engine for power generation is limited due to the physical/thermodynamical properties of the fluids. A comparative study of different working fluids for power generation including steam Rankine heat engine is desirable from the point of view of energy conservation. In **Chapter-IV** the author has studied the thermal modelling of the Rankine cycle heat engine for power generation with various refinements incorporating regeneration and internal/external superheating & recompression for improving the thermal efficiency of the heat engine cycle. Parametric studies based on component modelling and their influence on cycle efficiency have been investigated.

Chapter-V presents thermodynamic analysis of the Brayton cycle solar thermal power plant. The thermodynamic efficiency of a plant has been presented in terms of operating parameters such as compression pressure ratio, the pressure loss coefficient etc. In a modified version of the Brayton cycle in a solar power generating unit, a fuel assisted solar operated Brayton cycle for thermal power generation has been considered. The generated vapour from the flashing chamber is compressed, heated in a

regenerator using turbine exhaust steam and passed through a fuel fired superheater. From the thermodynamic study it is found that the solar energy input upto 15 to 20% is used for power generation with a fuel assisted superheater. As compared with fuel assisted Rankine power cycle, the present proposition gives higher efficiency and requires less fuel per unit power produced with a reduced superheater volume. A parametric study of the modified Brayton cycle is presented in this chapter.

The **Chapter-VI** presents need, potential and constraints of Stirling engines for Indian conditions [Sootha, Mohan & Singh, 1990]. One possible set of design criteria has been outlined by comparison with boiler-steam engine and gasifier-duel fuel engine routes. The result could be substantial softening of the design requirements of a candidate Stirling engine which could mean that manufacturing processes required could be simplified, costs could be reduced and the engines could be easily maintained. In furtherance, the thermodynamic analysis of a Stirling cycle solar thermal power system has been undertaken and effects of receiver temperature, type of collector and their optical efficiency on overall thermodynamic efficiency has been studied.

It is evident from the Chapter-I, that the parabolic trough technology based solar thermal power generation is the only commercially available technology [Kearney et al., 1991]. Therefore, design conceptualisation of a 30 MWe solar thermal

power plant has been prepared which includes capacity selection; determination of collector area & land area required; orientation & lay-out of collectors; selection of heat exchangers, heat transport medium, heat storage; Turbine generator type, back-up; gross-electricity generation etc. In furtherance, economic evaluation of solar thermal power generation for Indian conditions [Singh & Kaushik, 1994a] has been conducted. The study incorporates case study of parabolic trough collector technology for power generation in 30 MW scale taking into account various options such as Solar Alone and Solar Hybrid. Sensitivity analysis by varying plant load factor, discount rate and the capital cost etc. has also been carried out for both-the Solar Alone and the Solar Hybrid case. Therefore, the design conceptualisation and economic evaluation of solar thermal power generation in Indian conditions has been presented in the **Chapter-VII.**

The overall conclusions of `Techno-economic assessment and thermodynamic studies on solar thermal power generation' have been presented in **Chapter-VIII.**

The above work has partially appeared in the form of following publications and research papers.

1. **"Optimum Operating Temperature and Efficiency of Solar Thermal Power Generation", N.Singh** and S.C.Kaushik, J. of Heat Recovery Systems & CHP (In Press).

2. **"Techno-economic Evaluation of Solar Thermal Power Generation: A Case Study for Indian Conditions", N.Singh** and S.C.Kaushik, International Journal of Solar Energy (In Press).

3. **"Thermal Modelling and Energy Conservation Studies of Rankine Cycle System with Regenerative Heat Exchanger",** S.C.Kaushik, A.Dubey and **N.Singh**, J. of Heat Recovery Systems & CHP, Vol.14, No.1, p.67-77, 1994.

4. **"Environmentally Compatible Technology: Solar Thermal Power Generation", N. Singh,** Journal of Energy Opportunities, p.16-17, Dec. 1989.

5. **"Stirling Engines-Need, Potential and Constraints for Indin Conditions",** G.D.Sootha, S.Mohan and **N.Singh,** Vth International Stirling Engine Conference, paper No.71, Yugoslavia, May 1991.

6. **"Thermodynamic Analysis of a Brayton Cycle for Solar Thermal Power Generation", N.Singh** & S.C.Kaushik (In Communication).

7. **"Design, Testing and Performance of 50 kW Solar Thermal Power Plant", N.Singh** et al., National Solar Energy Convention, Udiapur (India), p.355-359, 1989.

8. **"Thermodynamic Analysis of a Stirling Cycle for Solar Thermal Power Generation", N.Singh** & S.C.Kaushik (In Communication).

9. **"Technology Assessment and Economic Evaluation of Solar Thermal Power Systems: A State of Art Report", N.Singh** and S.C.Kaushik, Nov. 1993.

10. **"Optimisation of Back-up Capacity in Fossil Fuel-Solar Thermal Hybrid Power Plants",** S.Mohan, **N.Singh** & G.D.Sootha, Seminar on Solar Power Systems, Alustha (USSR), April 25-26, 1991.

In addition, the author has also contributed in the following publications:

1. **"Transient Analysis for Trouble Shooting in 50 kW Solar Thermal Power Plant, Gwal Pahari", N.Singh** et al., National Solar Energy Convention, Udaipur (India), p.361-365, 1989.

2. **"Design Considerations in MW Scale Solar Thermal Power Plants"**, S.Mohan, **N.Singh,** R.S.Sharma, Urja Bharati (Special Issue on Solar Energy), Vol.5, No.1, p.44-45, 1994.

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