TECHNO-ECONOMICS OF
CONCENTRATING SOLAR POWER IN INDIA

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by

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Certificate

This is to certify that the thesis entitled **Techno-economics of Concentrating Solar Power in India** being submitted by **Mr. Tarun Kumar Aseri** to Indian Institute of Technology Delhi in fulfilment of the requirements for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him under our guidance and supervision at **Department of Energy Science and Engineering, Indian Institute of Technology Delhi**. The results obtained herein have not been submitted in part or in full to any other University or Institute for the award of any degree to the best of our knowledge.

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Abstract

An attempt toward a techno-economic assessment of concentrating solar power (CSP) plants in India has been made in the present study so as to facilitate a comparison with other renewable (solar PV and onshore wind) and fossil fuels based electricity generation. Feasibility assessment of wet cooling at potential locations for CSP plants in India has been made and the impact of the other condenser cooling options (dry and hybrid) on the levelized cost of electricity (LCOE) has been studied. Using an inventory of materials based approach, the capital costs of CSP plants have been estimated and the same have been used to estimate the LCOE for CSP plants in India while taking into account the effect of location, nominal capacity of the CSP plants as well as capacity (hours) of thermal energy storage. A preliminary attempt has also been made to assess the potential of capital cost reduction with indigenization and adoption of emerging technologies. The extent of some of potential incentives such as viability gap funding, interest subsidy, generation-based incentives, investment/production tax credit, etc. required for the LCOE to match with average power purchase cost (APPC) of the utilities has also been estimated. Since CSP plants with thermal energy storage (TES) can deliver electricity during peak demand periods, the break-even value of time-of-delivery tariff for the electricity delivered has also been estimated.

Results obtained show that only 28 (out of a total 95) locations in India with potential for CSP generation are suitable for wet-cooled CSP plants (while harvesting both rainwater and groundwater). Compared to parabolic trough solar collector (wet/dry), the central tower receiver based plants with the provision of TES can deliver electricity at relatively lower LCOE. With the adoption of emerging CSP technologies and indigenization of some of the components, there is potential for reduction in LCOE up to 40.3%. The extent of incentivization (even with combination of two/three incentives) required to achieve APPC is found to be very large in many cases. With increasing APPC for electricity distribution utilities, a provision of levying time-of-delivery tariffs for electricity delivered by CSP plant with the provision of TES

is likely to improve the financial attractiveness considerably. From the analysis and results presented in the thesis it is possible to identify locations in India where wet cooling of condenser in CSP plants is feasible. It is also noted that even with indigenization and adoption of emerging CSP technologies the LCOE is likely to be significantly higher that the average power purchase cost of distribution utilities and thus, suitable incentivization measures would be required in the initial phase. Appropriate time-of-use pricing of electricity delivered by the CSP plants with thermal storage would be directly relevant in this regard.

सारांश

इस शोध ग्रन्थ में भारतवर्ष में केंद्रित सौर ऊर्जा (सीएसपी) संयंत्रों के तकनीकी–आर्थिक मूल्यांकन की दिशा में एक प्रयास किया गया है ताकि अन्य नवीकरणीय (सौर फोटोवोल्टिक और तटवर्ती पवन) और जीवाश्म ईंधन आधारित विद्युत उत्पादन विकल्पों के साथ तुलना की जा सके। भारत में सीएसपी संयंत्रों के लिए संभावित स्थानों पर आर्द्र शीतलन की व्यवहार्यता का मूल्यांकन किया गया है और विद्युत की समतलित लागत (एलसीओई) पर अन्य संघनित्र शीतलन विकल्पों (शुष्क और संकर) के प्रभाव का अध्ययन किया गया है। सीएसपी संयंत्रों की पूंजीगत लागत का अनुमान लगाने के लिए, स्थान के प्रभाव, सीएसपी संयंत्रों की निर्धारित क्षमता के साथ–साथ तापीय ऊर्जा संचयक की क्षमता (घंटे) को ध्यान में रखते हुए, सामग्री की सूची आधारित विधि का उपयोग करते हुए भारत में सीएसपी संयंत्रों के लिए एलसीओई का अनुमान लगाया गया है। स्वदेशीकरण और उभरती प्रौद्योगिकियों को अपनाने के साथ पूंजीगत लागत में कमी की संभावना का आकलन करने के लिए एक प्रारंभिक प्रयास भी किया गया है। सीएसपी संयंत्रों की एलसीओई का विद्युत वितरण कंपनियों के औसत विद्युत खरीद लागत (एपीपीसी) के बराबर लाने हेतु आवश्यक संभावित प्रोत्साहनों जैसे व्यवहार्यता अंतराल वित्तपोषण, ब्याज में छूट, उत्पादन–आधारित प्रोत्साहन, निवेश/उत्पादन आधारित आय कर में छूट इत्यादि की आवश्यकता का अनुमान भी लगाया गया है।। चूंकि तापीय ऊर्जा संचयक (टीईएस) वाले सीएसपी संयंत्र अधिकतम मांग अवधि के दौरान विद्युत वितरण कर सकते हैं, इसलिए आपूर्ति की गई विद्युत के लिए आवश्यक समय–आधारित–वितरण दर का भी अनुमान लगाया गया है।

प्राप्त परिणामों से पता चलता है कि सीएसपी उत्पादन की क्षमता वाले भारत में केवल 28 (कुल 95 में से) स्थान आर्द्र शीतलन (वर्षा जल और भूजल दोनों का संचयन) आधारित सीएसपी संयंत्रों के लिए उपयुक्त हैं । परवलयिक गर्त सौर संग्राहक (आर्द्र/शुष्क) की तुलना में, टीईएस के प्रावधान वाले केंद्रीय स्तंभ अवशोषक आधारित संयंत्र अपेक्षाकृत कम एलसीओई पर विद्युत आपूर्ति कर सकते हैं। उभरती सीएसपी प्रौद्योगिकियों को अपनाने और कुछ घटक के स्वदेशीकरण के साथ, एलसीओई में 40.3% तक की कमी की संभावना है। एपीपीसी को हासिल करने के लिए आवश्यक प्रोत्साहन की सीमा (दो/तीन प्रोत्साहनों के संयोजन के साथ भी) कई मामलों में बहुत अधिक पाई गयी है। विद्युत वितरण संस्थानों के लिए एपीपीसी बढ़ने के साथ, टीईएस के प्रावधान के साथ सीएसपी संयंत्र द्वारा वितरित विद्युत के लिए समय–आधारित–वितरण दर लगाने के प्रावधान से वित्तीय आकर्षण में काफी सुधार होने की संभावना है। शोध प्रबंध में प्रस्तुत विश्लेषण और परिणामों से भारत में उन स्थानों की पहचान करना संभव है जहां सीएसपी संयंत्रों में संघनित्र का आर्द्र शीतलन संभव है। स्वदेशीकरण और उभरती सीएसपी प्रौद्योगिकियों को अपनाने से एलसीओई के विद्युत वितरण कंपनियों की औसत विद्युत खरीद लागत की तुलना में काफी अधिक होने की संभावना है, अतः प्रारंभिक चरण में उपयुक्त प्रोत्साहन उपायों की आवश्यकता होगी। तापीय ऊर्जा संचयक के साथ सीएसपी संयंत्रों द्वारा वितरित विद्युत के लिए उचित समय–आधारित–वितरण दर का निर्धारण इस संबंध में प्रासंगिक होगा।

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Nomenclature

Symbols

A	Rainfall catchment area (m^2)
A_p	Total area of CSP plant (m^2)
AC	Annual cost (Million US $)
AGW	Annual groundwater (m^3)
A_{sf}	Area of solar field (m^2)
C_0	Capital cost of CSP plant (Million US $)
C_w	Amount of working capital (Million US $)
d	Discount rate (Fraction)
$F_{CO2\text{-}eq}$	$CO_{2\text{-}eq}$ emission factor (Fraction)
F_d	Debt in capital cost (Fraction)
F_e	Equity in capital cost (Fraction)
f_{etm}	Cost of equipment/tools/machinery (Fraction)
f_o	Cost of overheads (Fraction)
F_{vgf}	Viability gap fund as a fraction of capital cost (Fraction)
GA	Geographical area of a district (m^2)
GWP	Groundwater potential (m^3)
H_{tes}	Hours of thermal energy storage (Hours)
HD	Heat duty of heat exchanger (MW_{th})
I_d	Annual rate of interest on debt (Fraction)
I_{is}	Annual rate of interest subsidy (Fraction)
I_{tax}	Annual rate of income tax as applicable for project developer/equity investor (Fraction)
LCOE	Levelized cost of electricity (US $/MWh)
$LCOE_t$	Target value of LCOE (US $/MWh)
m	Mass of material (kg)
n	Useful life of the CSP plant (Years)
NC	Nominal capacity (MW)
P	Price of material (INR/kg)
R_{ad}	Rate of accelerated depreciation (Fraction)
R_{ceru}	Price of certified emission reduction unit (US$/t$CO_2$)
R_e	Annual rate of return on equity investment (Fraction)
R_{gbi}	Rate of generation based incentive (US$/MWh)
R_{itc}	Rate of investment tax credit (Fraction)
R_{ptc}	Rate of production tax credit (Fraction)
RF	Annual rainfall (mm)
RHP	Rainwater harvesting potential (m^3)
ROC	Runoff coefficient (Fraction)
SM	Solar multiple

TC	Thermal capacity of solar field (MWh)
TESC	Thermal energy storage capacity (MWh)
W_{gross}	Gross nominal capacity (MW)

Greek symbols

η_{pb}	Efficiency of power block
η_{tes}	Efficiency of thermal energy storage system

Acronyms

AD	Accelerated depreciation
APPC	Average power purchase cost
BOP	Balance of plant
CERC	Central Electricity Regulatory Commission
CERU	Certified emission reduction unit
CGWB	Central ground water board
CSP	Concentrating solar power
CTR	Central tower receiver
CUF	Capacity utilization factor
DNI	Direct normal irradiance
EPC	Engineering, procurement and construction
ET	Euro trough
FiT	Fee-in-tariff
GBI	Generation based incentive
HTF	Heat transfer fluid
INR	Indian rupees
IRENA	International renewable energy agency
IS	Interest subsidy
ITC	Investment tax credit
ITRID	Income tax rebate on interest paid on debt component
LCOE	Levelized cost of electricity
LFR	Linear Fresnel reflector
LR	Learning rate
MEIL	Megha Engineering & Infrastructures Limited
NAEO	Net annual electricity output
NC	Nominal capacity
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Data Base
O&M	Operation and maintenance
PB	Power block

PD	Parabolic dish
PTC	Production tax credit
PTSC	Parabolic trough solar collector
PV	Photovoltaic
REC	Renewable energy certificate
RPO	Renewable purchase obligation
SAM	System Advisor Model
SCA	Solar collector assembly
SGWD	Stage of groundwater development
SM	Solar multiple
TES	Thermal energy storage
ToD	Time-of-delivery
UT	Ultimate trough
VGF	Viability gap funding
WACC	Weighted average capital cost