MODELLING AND SIMULATION

OF

RENEWABLE ENERGY SOURCES

RAJESH KUMAR

INSTRUMENT DESIGN DEVELOPMENT CENTRE
INDIAN INSTITUTE OF TECHNOLOGY, DELHI
June 2015

© Indian Institute of Technology Delhi (IITD), New Delhi, 2015

MODELLING AND SIMULATION OF RENEWABLE ENERGY SOURCES

by

Rajesh Kumar
Instrument Design Development Centre

Submitted
In fulfillment of the requirement of the degree of
DOCTOR OF PHILOSOPHY

to the

Indian Institute of Technology, Delhi
India
June 2015

CERTIFICATE

This is to certify that the thesis entitle "**Modelling and Simulation of Renewable Energy Sources**" submitted by Mr. **Rajesh Kumar** for the award of the degree of the **Doctor of Philosophy** to the Indian Institute of Technology Delhi is a record of the bonafide research work he has carried out under my supervision. The results contained in this thesis have not been submitted to any other University or Institute for award of any degree or diploma.

Dated 19th June , 2015

(A.K.Agarwala)
Chief Design Engineer
Instrument Design Development Centre
Indian Institute of Technology Delhi
New Delhi -110016
India

ACKNOWLEDGEMENTS

The present work was made possible through support from many people. I acknowledge the contribution from my colleagues at IIT Delhi and Ministry of Science and technology. I gratefully express my sincere gratitude to supervisor and mentor, Shri A.K.Agarwala, for his valuable guidance, constant encouragement and support throughout this work. In particular, I would like to thank Shri A.K.Agarwala for his proper supervision and guidance, and for reading and correcting all the manuscripts.

I am very grateful to Secretary, Department of Scientific and Industrial Research and Secretary, Department of Science & Technology for putting trust in me to work at IIT Delhi for thesis work and allowing me to spare time for research work.

I am thankful to Dr.N.K.Jain, Dr.G.N.Tiwari, Dr. D.T.Shahani, Dr. Gufran Saheed Khan and Dr. A.L. Vyas and other faculty members of IIT Delhi for their guidance, internal assessment and support for research work. I also acknowledge Shri V.K.Gandhi, from lab and other staff of Instrument Design and Development Centre (IDDC) for their kind support. I am thankful to Dr. Anand Kamavisdar, Scientist, Department of Science & Technology, for his support in reviewing the research work..

Special thanks go to my wife and son for their love, care and moral support. I also acknowledge my parents and brother, during my academic progression. All friends and relatives are thanked for their contribution to this work.

Rajesh Kumar

ABSTRACT

Diffusion of renewable energy technologies (RETs) is governed by the status of technology in terms of efficiency and techno-economical feasibility. Indian energy resources and distribution is governed by individual states. The states conceptualise the central Government policy and plan for the deployment of resources for the development with special reference to sustainable environment. The proposed demand and supply energy model helps to provide more focus on the long term goals. The theory of diffusion modelling provides analysis of diffusion processes and path for growth rates of different technologies and underlying diffusion factors on innovation, policy and target of the particular states.

In this study, a methodology has been studied for sizing energy sources from solar, wind, hydro, geothermal. The hybrid power generation system is central to renewable energy source utilization. The purpose of this methodology is to predict the Solar- area, wind speed availability over seasons, flow of water, and battery bank for which the meteorological data on solar irradiation, air temperature, wind speed, underground heat etc are available. The characteristics of hybrid power generation system are used to analyse using MATLAB. The simulation model of the hybrid energy is considered by using the MARKAL model. A simulation analysis is performed to investigate a variety of energy sources and cost economic characteristics, distribution, environment and access to technology.

An energy probabilistic model is developed to provide a tool to assess the effects of different support mechanisms on the financial return of solar PV systems and solar thermal, wind turbine, small-scale hydroelectric and geothermal energy. Besides, the results from this model are used to compare the economic effectiveness of each mechanism in increasing the profitability of these projects. The model has considered the effect of the carbon credits on the net present value of

renewable projects and compared it with the other support Mechanisms like green certificate, governmental grants and secondary support mechanisms. The comprehensive energy model comprising cost effectiveness and performance of the support mechanisms for techno-economic feasibility is described. The construction of generalized templates is used so that the model can serve as a basis for generating the specific template to cater different energy sources.

This work focuses on developing an energy analysis, simulation and prediction model using an extensive data base available with NREL, CWet (NIWE), IMD and others on renewable energy resources in India, This model allows useful estimations of the renewable energy potential at any location; and also uses an algorithm for diversified renewable energy sources and building integrated hybrid projects. A statistical and analytical function makes comparative display of the same indicators of different RE sources, projects or indicators of the same project, leading to popularization of renewable energy saving in different areas.

The energy model incorporates the policy instrument on Renewable Energy Certificates (REC) and Perform, Achieve & Trade (PAT) mechanism. RECs are a policy mechanism to promote renewable energy based power generation in India. PAT is a market interactive mechanism for enhanced energy efficiency. These policy instruments are implemented in India in addition to Clean Development Mechanism (CDM).

Contents

List of Figures

List of Tables

List of Acronyms

BEE	Bureau of Energy Efficiency
CDM	Clean Development Mechanism
CERC	Central Electricity Regulatory Commission
CPP	Captive Power Plants
CPV	Concentrated Photovoltaic
CTF	Clean Technology Fund
CWET	Centre for Wind Energy Technology
DC	Designated Consumers
DENA	Designated Energy Auditors
ECBC	Energy Conservation Building Code
ESCert	Energy Savings Certificates
ESCO	Energy Service Company
ETS	Emission Trading Scheme
GEF	Global Environment Fund,
IDE	Integrated Development Environment
IEX	Indian Energy Exchange
IMD	Indian Meteorology Department
JNNSM	Jawaharlal Nehru National Solar Mission
MEM	Modified Econometric Mathematical model

MNRE	Ministry of New & Renewable Energy
MPEEE	Mathematical Programming Energy-Economy-Environment model
NLDC	National Load Dispatch Centre
NMEEE	National mission on Enhanced Energy Efficiency
NREL	National Renewable Energy Laboratory
OREM	Optimal Renewable Energy Mathematical model
PXIL	Power Exchange India Limited
SDA	State Designated Agencies
SEC	Specific Energy Consumption
SERC	State Electricity Regulatory Commission
SLDC	State Load Dispatch Centre
SPV	Solar photovoltaic
PAT	Perform, Achieve and Trade
RE	Renewable Energy
REC	Renewable Energy Certification
RPO	Renewable Purchase Obligation
UNFCCC	United Nations Framework Convention on Climate Change

List of Symbols

*	Multiplication
S	Solar irradiance kW/m^2
$f_b(s)$	Beta distribution function of s
α_s	parameter of the Beta distribution function
β_s	parameter of the Beta distribution function
μ	Mean of the observations
σ	Standard deviation of the random variable
N	Number of daylight (sunshine) hours
Φ	latitude of a location
δ	Declination angle
I_r	Solar radiation incident
I_{sc}	Solar constant
n	Day of the year from 1 to 365
θ_z	Zenith angle
H_o	Integrated daily extraterrestrial radiation
Ω	Sunset hour angle
β	Pitch angle of Wind Turbine
λ	Torque of Wind Turbine
P_w	Aerodynamic power of Wind Turbine

$C_p(\lambda,\beta)$	Power coefficient of Wind Turbine
V_t	Wind speed
V_c	Cut-in wind speed
V_R	Rated wind speed
V_F	Cut-out wind speed
P_R	Rated power of Wind Turbine
H_{hub}	Wind turbine hub height
H_{data}	Reference to a height
K_w	Rock hydraulic conductivity
υ	Speed fluid moving through a porous medium
H	Effective head of liquid
L	Head per meter of distance L along the flow direction
Q	Volume of water
A	cross-sectional area
q	One dimensional vertical heat flow
ΔT	Temperature difference
z	vertical height of storage
E_{PV}	Solar PV potential
I_R	Global solar radiation obtained from the surface of the solar cell array
P_V	Energy in the form of electrical voltage and current produced by solar cell array is
L	Inverter loss during conversion to usable energy L

T_{PV}	Substituted quantity of PAT for power conversion and smart grid technology
δ_{pv}	REC Certificate for the generation
ζ_{pv}	Coefficient of life span of product
E_{th}	Solar Thermal Potential
η_1	Solar energy heat collecting system efficiency
η_2	Solar heat exchanger heating system efficiency
Q_{uf}	Useful heat quantity of solar heat collecting system
T_{th}	Substituted quantity of PAT for power conversion and smart grid technology
δ_{th}	REC Certificate for the generation
ζ_{th}	Coefficient of life span of product
I_b	Beam radiation,
I_d	Diffused radiation
R_b	Conversion factors for beam radiation
R_d	Conversion factors diffuse radiation
R_r	Conversion factors reflected radiation
ρ	Reflected coefficient of the ground
P_{pv}	Power output from PV array
η_{pv}	Efficiency of PV system
A	Area of the solar array.
E_w	Wind Energy Potential
P_W	Wind turbine capacity factor

T_w	Factor of technology on Enhance efficiency and
δ_w	Impact of REC on the energy generation
ζ_w	Coefficient of life span of product
η_w	Efficiency of Wind turbine
A_w	Area of cross section of wind blade
P_{wt}	Wind power at time t
P_w	Wind power output
E_{gshp}	Geothermal Energy Potential
η_H	Heating condition system ratio of energy and efficiency
η_A	Air conditioning system ratio of energy and efficiency
δ_g	Substitution quantity of conventional energy and issue of REC
T_g	Substituted quantity of PAT for power conversion and smart grid technology
ζ_L	Coefficient of life span of product
T_f	Circulation fluid temperature in Kelvin;
Q_h	is heat injection/ extraction in Watts;
λ_{eff}	Effective thermal conductivity in W/Km;
H	Length of the borehole heat exchange in meter;
α	Thermal diffusivity in W/m K;
γ	Euler's constant (=0.5772);
R_{bh}	Borehole resistance in m K/W
Ti	Undisturbed ground temperature in K.

T_{ave}	Average between the inlet and outlet temperature in K;
T_o	Ground's natural temperature (◦C) at depth y (meter) at time t;
T_d	Mean Earth's surface-temperature (◦C) between the hottest and the coldest months;
A_d	Amplitude (◦C) of the Earth's surface temperature;
Ω	Frequency, rad/h
a	Thermal diffusivity, W/m◦C.
C_{bat}	Battery bank capacity
E_{load}	Electrical Load
η_{bat}	Battery Efficiency
H_n	Net available drop
V_{PV}	Water volume production of hydro-energy E_{HE}
h^t is	Water volume in the upper reservoir at time t, t=0 … t=T-1, (m^3);
$\hat{h}^t$	Water volume in the lower water reservoir at time t, t=0 … t=T-1 (m^3);
$\hbar^t$	Hydrogen volume in the hydrogen storage at time t, t=0 … t=T-1 (m^3).
u^t	Water flow that is spilled from the upper reservoir and is dedicated to energy production through the hydro-electric turbine, in time interval (t,t+1) ($m^3 s^{-1}$);
y^t	Water flow that is spilled from the upper reservoir and is dedicated to the water demand satisfaction, in time interval (t,t+1) ($m^3 s^{-1}$);
yl^t	Water flow that is spilled from the lower reservoir and is dedicated to the water demand satisfaction, in time interval (t,t+1)($m^3 s^{-1}$);
uh^t	Hydrogen flow that is extracted from the storage and used to produce energy in the fuel cell, in time interval (t,t+1) ($m^3 s^{-1}$);

yh^t	Hydrogen flow that is dedicated to hydrogen demand satisfaction, in time interval (t,t+1) (m^3 s^{-1});
Qh^t	Water flow that enters the upper water reservoir in time interval (t,t+1) (m^3 s^{-1});
Ql^t	Water flow that enters the lower water reservoir from hydro-electric power plant in time interval (t,t+1) (m^3 s^{-1});
ul^t	Water flow that is pumped from the lower water reservoir, in time interval (t,t+1) (m^3 s^{-1}), to be sent to the upper reservoir
Qel^t	Hydrogen flow that enters the hydrogen storage from the electrolizer in time interval (t,t+1) (m^3 s^{-1})
E_3^t	Electric energy produced from the wind farm
η_1 η_2	Parameters of the electrolyze plant
H_2	Difference between the altitudes of the upper water reservoir and the hydroelectric turbine site (m);
g	Gravity acceleration constant (kg/ m^2)
μ_{ht}	Hydro-electric turbine efficiency
LHV	Hydrogen lower heating value (kWh/kg)
η_{FC}	Fuel cell efficiency
D^t	Hourly energy demand to be satisfied in time interval per residential unit (t,t+1), t=0, …. ,T-1 (kWh);
DWh^t	Water demand to be satisfied in time interval (t,t+1) from the upper reservoir (m^3 s^{-1})
DWl^t	Water demand to be satisfied in time interval (t,t+1) from the lower reservoir (m^3 s^{-1});
DH^t	Hydrogen demand to be satisfied in time interval (t,t+1), (m^3 s^{-1});

N	Total Potential,
p	Coefficient of innovation (or coefficient of external influence); and
q	Coefficient of imitation (or coefficient of internal influence).
x(t)	Function of the marketing-mix variables at time period t
I_{out}	Current output from panel
V_{out}	Voltage output from Panel
I_{rated}	Rated panel current
V_{rated}	Rated panel voltage
I_{ue}	Useful current
V_{ue}	Useful voltage
η	Efficiency
C_t	Cost of technology/ PV
L	Life of the Technology/ PV
C_o	Cost of the first unit produced,
b	Experience index