

# Renewable Energy



# Renewable Energy:

## *Selected Issues Volume II*

Edited by

Manuel Pérez-Donsión, Silvano Vergura  
and Gianpaolo Vitale

Cambridge  
Scholars  
Publishing



Renewable Energy: Selected Issues Volume II

Edited by Manuel Pérez-Donsión, Silvano Vergura and Gianpaolo Vitale

This book first published 2016

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

Copyright © 2016 by Manuel Pérez-Donsión, Silvano Vergura,  
Gianpaolo Vitale and contributors

All rights for this book reserved. No part of this book may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the copyright owner.

ISBN (10): 1-4438-8524-X

ISBN (13): 978-1-4438-8524-9

As a two-volume set:

ISBN (10): 1-4438-8803-6

ISBN (13): 978-1-4438-8803-5

# TABLE OF CONTENTS

Foreword .....	xiv
Outline of the Book .....	xvii
To Whom this Book is Addressed .....	xviii
Acknowledgments .....	xix
How to Use this Book.....	xxi
Biographies of the Editors .....	xxii

## Volume I

### Part I: Data Management

Chapter One.....	2
Data Clustering for Accurate Energy Planning of a Photovoltaic Plant A. Di Piazza, M. Carmela Di Piazza, G. Vitale	
Chapter Two .....	19
Forecast of Hourly and Daily Solar Irradiance using Artificial Neural Networks S. Seme, G. Štumberger	
Chapter Three .....	31
Energy Forecast in a Large PV Plant under Partial Shading by Kriging-based Approach A. Di Piazza, M. Carmela Di Piazza, G. Vitale	

### Part II: Distributed Generation Issues

Chapter Four.....	56
Grid Synchronization of Renewable Energy Sources in Distributed Generation Systems C. J. Ramos, A. P. Martins, A. S. Carvalho	

Chapter Five .....	71
An Assessment of Renewable Energy Generation in a Conventional Steam Power Plant	
J. Buchta	
Chapter Six .....	85
Estimation and Synchronization Techniques for Power Electrical Signals	
G. Fedele, A. Ferrise	
Chapter Seven.....	117
Voltage Control Capability of Distributed Generation in Low Voltage Network	
F. Sulla, J. Björnsted, O. Samuelsson	
Chapter Eight.....	132
Effect of Distributed Generation in the Location of Faults by means of Impedance-based Methods	
J. Meléndez, S. Herraiz, J. Faig, J. Sanchez	
Chapter Nine.....	150
Wind Park Power Control for Improving Frequency Stability of an Integrated Power Grid	
S. Liu, Y Zhou	
Chapter Ten .....	170
Management of Voltage Unbalances: New Control Strategies for Permanent Magnet Synchronous Wind Generators	
F. Belloni, R. Chiumeo, C. Gandolfi	
Chapter Eleven .....	188
Impact Assessment of Grid Connected Photovoltaic Systems on the UK Low Voltage Distribution Network	
S. Ali, N. Pearsall, G. Putrus.	
<b>Part III: Fuel Cells and Electric Vehicles</b>	
Chapter Twelve .....	200
Urban Bus based on Hydrogen and PV	
I. Zamora, J.I. San Martín, J. Garcia-Villalobos, F.J. Asensio, V. Aperribay	

Chapter Thirteen .....	218
Analysis of Solid Oxide Fuel Cells by a Simulation Model	
I. Zamora, J.I. San Martín, A. J. Mazón, V. Aperribay, F.J. Asensio	
Chapter Fourteen .....	234
Performance Analysis of a PEM Fuel Cell System based on ANN	
I. Zamora, J.I. San Martín, J. Garcia-Villalobos, P. Eguía, V. Aperribay	
Chapter Fifteen .....	253
Development of Model Based Controllers for Fuel Cell Systems	
K.K.T. Thanapalan, J. G. Williams	
<b>Part IV: Hybrid Systems</b>	
Chapter Sixteen .....	276
Energy Efficiency Improvement by Polygeneration with Fuel Cells	
J.I. San Martín, I. Zamora, V. Aperribay, P. Eguía, J. Garcia-Villalobos	
Chapter Seventeen .....	292
Levelling PV Power Variations by Optimal Capacity of ESS	
in the Operation of a PV-Diesel Hybrid System	
M. Datta, T. Senjyu, T. Funabashi	
Chapter Eighteen .....	308
Design of an Efficient Hybrid System for Electricity Production	
with Supervisory Control	
J. M. Figueiredo	
Chapter Nineteen .....	327
Establishment of Switching Thresholds for Electrolyser in Stand-alone	
Hybrid Photovoltaic-wind system with Hydrogen Storage	
A. J. Calderón Godoy, M. Calderón Godoy, I. González, Pérez,	
A. Ramiro González.	
Chapter Twenty .....	347
Improving PV Production with Energy Storage by a Solar Forecast	
Control System	
D. Diaz Varela, J. A. Souto Gonzalez, Angel Rodriguez,	
Santiago Saavedra, J. J. Casares, A. Garcia Loureiro, R. Varela,	
M. J. Rodriguez Legarreta.	

Chapter Twenty-One .....	360
Grid-tied Wind-PV Hybrid System with Energy Storage and Power Prediction: A Case Study	
H. Bludszuweit, J. A. Domínguez, J. L. Bernal	
Chapter Twenty-Two.....	379
A Novel Multi-loop Control Algorithm for a Hybrid PV Energy Farm	
A. M. Sharaf, I. Hakki Altas, E. Ozkop	
Chapter Twenty-Three.....	402
Construction and Techno-economic Analysis of a Small-scale Hybrid RES Power System of Wind Generator and Photovoltaic Panels	
I. Yiakoumi, A. Safacas	
<b>Part V: Microgrids</b>	
Chapter Twenty-Four .....	420
Multi-Agent Based Operation and Control of Micro-Grid with Renewable Energy Power Sources Including Energy Storage Device	
Takashi Hiyama	
Chapter Twenty-Five.....	440
Changeover Control of Stand-alone Power Supply Systems with Fuel Cells	
S. D'Arco, R. Rizzo, P. Tricoli	
Chapter Twenty-Six.....	455
Steady State and Dynamic Analysis of a MicroGrid System	
A. G. Madureira, C. L. Moreira, H. M. Costa, J. A. Peças Lopes	
Chapter Twenty-Seven .....	471
Creation of a Stability Index for a Microgrid	
I. Vokony	
Chapter Twenty-Eight .....	481
Microgrid SCADA based on OPC Communication Standard and Web Interfaces	
E. Álvarez, A. M. Campos, R. García, S. González, C. Diez	

Chapter Twenty-Nine .....	497
Time Delays Compensation in the Centralized Control System of a Smart Grid for Providing System Ancillary Services	
R. Angelino, A. Bracale, G. Carpinelli, M. Mangoni, D. Proto.	
Chapter Thirty .....	520
An Energy Management System for Virtual Power Plants	
J.A. Barbosa, R.P.S. Leão, R.F. Sampaio, G.C. Barroso, F.L.M. Antunes	
Chapter Thirty-One .....	539
Economic Viability Analysis of Optimal Power Flow in Microgrids	
J. R. Martínez, M. A. Saidel, E. A. Fadigas	

## Volume II

### Part VI: Solar Technologies

Chapter Thirty-Two .....	2
Modeling the Primary Loop of a Concentrating Solar Power Plant	
S. Vergura	
Chapter Thirty-Three .....	24
Optimal Design in Virtual Prototyping Environment of a Dual-Axis Pseudo-Equatorial Solar Tracker	
C. Alexandru, M. Comșit	
Chapter Thirty-Four .....	40
A Reduced-order PV Model Parameter Identification Solution by using a Linear Regression-based Approach	
M. C. Di Piazza, G. Vitale	
Chapter Thirty-Five .....	58
Application of the AHP and TOPSIS Methods to the Assessment of Photovoltaic Technologies	
J. Miguel Sánchez-Lozano, M. Socorro García-Cascales, Nieves Espinosa, Antonio Urbina	
Chapter Thirty-Six .....	75
Off-grid PV System to Supply a DC Nanogrid	
A. Freitas, F. Antunes, S. Dahler, E. Miniero, F. Sergio.	

Chapter Thirty-Seven .....	105
Optimal Dual Junction Mechanically Stacked Solar Cells	
Ian Mathews, Donagh O'Mahony, Declan Gordon, Nicolas Cordero, B. Corbett, A. P. Morrison	
Chapter Thirty-Eight .....	122
Comparative Analysis between the Mono-axis and Dual-axis Tracking Systems used for a PV String	
C Alexandru, I. N. Tatu	
Chapter Thirty-Nine .....	134
Load Cases Evaluation for a Gear Based Azimuthal Photovoltaic Tracker Under Wind and Weight Action	
R. Velicu, B. Butuc, G. Moldovean	
Chapter Forty .....	150
Solar Photovoltaic Water Pumping System with a Linear Reluctance Actuator for Developing Countries	
P. Andrada, J. Castro	
<b>Part VII: Power Electronics for Renewable Energies</b>	
Chapter Forty-One .....	166
A New Vector Hysteresis Current Control Applied on Three-level NPC- VSI for Wind Conversion System	
T. Ghennam, K. Aliouane, K. Marouani, E. Berkouk, B. Francois	
Chapter Forty-Two .....	192
Dual Converters with Synchronized Pulse-width Modulation for Transformer-Based Photovoltaic Installations	
V. Oleschuk, V. Ermuratskii	
Chapter Forty-Three .....	206
Power Converter for Photovoltaic Panels with Uninterruptible Power Conditioner Providing Ancillary Services	
A. Filguera Vizoso, L. Piegari, P. Tricoli, D. Sharifi	
Chapter Forty-Four .....	229
Efficiency Analysis of Low Power Grid Connected Photovoltaic Systems	
A. P. Martins	

**Part VIII: Wind and Marine Power Generation**

Chapter Forty-Five .....	248
Potential for Exploiting the Renewable Marine Energies in Galicia	
P. B. González López, A. Álvarez García, C. Anido Martínez.	
Chapter Forty-Six .....	262
Investigating the Flow Conditions and Wake Interactions of Momentum-Reversal-Lift Tidal Turbine using CFD	
M. Gebrelasse, G. Tabor, M. Belmont	
Chapter Forty-Seven.....	279
Wind Harvesting Schemes based on the Reuse of Low-power Electrical Equipment	
J.S Artal., F.J. Arcega, A. Usón	
Chapter Forty-Eight.....	296
Wind Turbine Optimization for a Permanent Magnet Synchronous Generator (PMSG)	
A. Martinez, A. Ribas, J. Vergauwe	
Chapter Forty-Nine.....	313
Aerodynamic and Structural Evaluation of Horizontal Axis Wind Turbines with Rated Power Over 1 MW	
S. Laín, B. Quintero, Y. López	
Chapter Fifty.....	329
Simulation of the Aerodynamic Behaviour of a Micro Wind Turbine	
J. M. M. Monteiro, J. C. Páscoa, F. M R. P. Brójo	
Chapter Fifty-One.....	341
Noise Interference Phenomena in Monitoring Systems for Offshore Wind Turbines	
F. Arteche, F.J. Arcega, M.C. Esteban, M. Iglesias	
Chapter Fifty-Two .....	358
Collection and Amplification of Vertical Wind in Urban Building Façades by Cornice Modular Wind Collector	
J. C. Sáenz-Díez, J. Blanco, M. Pérez, J. M. Blanco, E. Martínez, E. Jiménez	

Chapter Fifty-Three .....	369
Asynchronous Generator with Inverter V. Bršlica	
Chapter Fifty-Four .....	392
Transient Analysis of Induction Generator and PWM Inverter Connected to a Weak Grid H. Bludszuweit, J. A. Domínguez, M. García	
<b>Part IX: Miscellanea</b>	
Chapter Fifty-Five .....	410
Renewable Energy Generation and Demand Side Management for Photovoltaic Optimization in Singular Apartment Buildings E. Jiménez, J. C. Sáenz-Díez, Juan Manuel Blanco, Ignacio Latorre, Eduardo Martínez, Mercedes Pérez	
Chapter Fifty-Six .....	424
Heat Transfer Analysis of Spherical Cell Photovoltaic Modules used in Energy Harvesting Applications A. M. Morega, A. Negoiaş, M. Morega	
Chapter Fifty-Seven.....	440
Public Water Supply Use for Micro Power Generation S. Ramos, A. Gomes, M. Cardoso, L. Castanheira	
Chapter Fifty-Eight.....	452
Secant Method with IPPD Table to Optimize Fuel Consumption of a Cogeneration Multi Machines System F. Alkhalil, F. Colas, P. Degobert, B. Robins	
Chapter Fifty-Nine.....	467
Quality Control Tests and Fault Detection in the Manufacturing Process of Form-wound Coils: A Case Study M.G. Melero, F. Pedrayes, J. Norniella, C.H. Rojas, M.F. Cabanas, G. Alonso, J. M. Cano, J.M. Barrera	
Chapter Sixty .....	487
Thermodynamics of Power Yield in Thermal, Chemical and Electrochemical Systems S. Sieniutycz	

Chapter Sixty-One .....	507
Solubility of Renewable Fuel Blends	
E. Torres-Jimenez, M. P. Dorado, B. Kegl	
Chapter Sixty-Two .....	520
Energy and Environment Model for the Electrical Industry: The Case of Spain	
M. Á. Verdejo, J. Fernández, M. Durán	
Chapter Sixty-Three .....	539
Study about the Opportunity to Use Different Renewable Energy Sources to Supply Residential Consumers	
F. D. Surianu, I. Borlea, D. Jigoria-Oprea, B. Lustrea	
Chapter Sixty-Four .....	554
Assessment of the Energy Production of a Farm Scale Anaerobic Digestion Plant	
A. Gagliano, F. Patania, F. Nocera, A. Galesi	
Chapter Sixty-Five.....	572
Properties of Energy Storage Technologies	
J. I. San Martín, I. Zamora, P. Eguía, V. Aperribay, J. Garcia-Villalobos	
Chapter Sixty-Six .....	591
Reliability Issues of Renewable Energy Based Power Systems for Telecommunications	
E. Ribeiro, A. J. M. Cardoso, C. Boccaletti	
Chapter Sixty-Seven.....	604
Selection of Cogeneration Alternatives for a Hospital: A Case Study	
J. Carcedo, C. J. Renedo, I. Fernández, A. Arroyo, F. Ortiz	
Chapter Sixty-Eight.....	623
Facilitation of Wind Generated Electricity using Price Responsive Electric Water Heating	
P. Finn, C. Fitzpatrick, L. Relihan	
Chapter Sixty-Nine.....	637
Simulation and Control of a Solar Thermal Plant	
J. Gall, D. Abel, N. Ahbrink, R. Pitz-paal, J. Andersson , M. Diehl, C. Teixeira Boura, M. Schmitz, B. Hohhschmidt	



**PART VI:**  
**SOLAR TECHNOLOGIES**

# CHAPTER THIRTY-TWO

## MODELLING THE PRIMARY LOOP OF A CONCENTRATING SOLAR POWER PLANT

SILVANO VERGURA<sup>1</sup>

### Abstract

A Matlab based model of the primary loop of a Concentrating Solar Power plant (CSP) is proposed. The modelled system considers the technology of parabolic troughs with a binary mixture of salts as the heat transfer fluid. The model is based on the layout of a pilot project to be implemented in the South of Italy, but it can be also used for different typologies of CSP, because it was implemented as a Graphical User Interface (GUI), which allows input data to be modified. As that project also contains thermal storage, the input and output temperatures are well defined. This choice removes the typical disadvantage of some renewable energy sources, i.e. the unpredictability of energy production. In this paper, only the primary loop of the whole system was modelled. The model permits the calculation of the main output variables of the primary loop: thermal performance, thermal power and thermal efficiency. The proposed model does not take into account transient phenomena and variable ambient conditions.

**Keywords:** CSP, Matlab model, molten salts, thermal efficiency, thermal power.

---

<sup>1</sup> Technical University of Bari, Dept. of Electrical and Information Engineering, st. E. Orabona 4, 70125 Bari, Italy. Email: [silvano.vergura@poliba.it](mailto:silvano.vergura@poliba.it)

## Nomenclature

$c_{ps}$	Specific heat of the mixture of salts, $\text{J kg}^{-1} \text{K}^{-1}$
$DNI$	Direct Normal Irradiation, $\text{kWh m}^{-2} \text{day}$
$GHI$	Global horizontal Irradiation, $\text{kWh m}^{-2} \text{day}$
$h_c$	External convective heat transfer coefficient, $\text{W m}^{-2} \text{K}^{-1}$
$h_d$	Heat transfer coefficient for low-density gas, $\text{W m}^{-2} \text{K}^{-1}$
$G_s$	Flow capacity, $\text{kg/s}$
$L, l$	Length, m
$Nu$	Nusselt number
$Pr$	Prandtl number
$Q_{ab,r}$	Losses of the absorber for radiation, W
$Q_{ab,c}$	Losses of the absorber for conduction, W
$Q_b$	Losses due to the metal bellows, W
$Q_{fluid}$	Thermal power, W
$Q_{g,r}$	Losses of the glass for radiation, W
$Q_{g,c}$	Losses of the glass for convection, W
$Q_{losses}$	Total losses, W
$r$	Radius, m
$Re$	Reynolds number
$S$	Heated surface, $\text{m}^2$
$T_g$	Temperature, K
$T_U$	Thermal performance, K
$\varepsilon_g$	Emissivity of the glass, 0.9
$\varepsilon_{ab}$	Emissivity of the absorber
$\eta$	Thermal efficiency
$\lambda$	Thermal conductivity, $\text{W m}^{-1} \text{K}^{-1}$
$\rho$	Density, $\text{kg m}^{-3}$
$\sigma$	Stefan-Boltzmann constant, $5.67 * 10^{-8} \text{W m}^{-2} \text{K}^{-4}$

## Introduction

The  $\text{CO}_2$  emissions are considered responsible for the climate changes on Earth. As these emissions are also produced by burning fossil fuels to produce electrical energy, many countries in the world are transforming their national electrical production systems, decreasing the electrical production deriving from fossil fuels and increasing that deriving from Renewable Energy Sources (RES). Among RES, solar technologies are motivating a large interest. Moreover, the green paper of the Commission of the European Communities [1] reports that half of the gas consumption

in the EU came from only three countries (Russia, Norway, Algeria) and the oil and gas prices nearly doubled in the EU over the past two years, with electricity prices following. Therefore, the EU strategy for energy is to reach the target of 20% of energy produced by RES until 2020. This paper focuses on Concentrating Solar Power plants (CSP) because they are acquiring an increasing interest, especially if built with thermal energy storage [2]-[3]-[4]. Moreover, economic issues for the CSP have been treated in order to verify the profits, the breakeven point and so on [5]-[6].

Inorganic nitrate salt mixtures are often preferred as a fluid because they offer a favourable combination of density, specific heat, very low chemical reactivity, vapour pressure and cost (\$0.40–\$0.90/kg) [6]. The three main candidate salts include: a) Hitec, a ternary mixture of  $\text{NaNO}_2$ ,  $\text{NaNO}_3$  and  $\text{KNO}_3$ ; b) Hitec-XL, a ternary mixture of  $\text{Ca}(\text{NO}_3)_2$ ,  $\text{NaNO}_3$ , and  $\text{KNO}_3$ ; c) a binary salt mixture of  $\text{NaNO}_3$  and  $\text{KNO}_3$ . The latter salt has the lowest cost and the minimum inventory temperature is at least  $80^\circ\text{C}$  above the freezing point; therefore, it will be considered in this paper. Obviously, the heat transfer fluid must be chosen taking also into account the Operation and Maintenance (O&M) costs. A detailed analysis of the O&M costs related to a CSP fed by molten salts is reported in [7], where important issues are considered, such as: routine freeze protection, solar field preheat methods, collector loop maintenance and the selection of appropriate materials for piping and fittings.

The CSPs can be categorized into three main technologies, based on the process of collecting and concentrating solar radiation [8]: a) Parabolic Trough, b) Solar Tower for Central Receiver, c) Parabolic Dish. There is also a fourth technology (Linear Fresnel Reflector), but it is less common than the previous ones.

The first one uses parabolic trough shaped mirrors to concentrate the incident Direct Normal Irradiation (DNI) onto a receiver tube which is placed at the focal line of the trough. This is the most commercial technology for CSPs because it is the most mature technology. As this technology is considered in the paper, an in depth description is reported in the next section.

In the Solar Tower technology, the solar collector field contains a radial arrangement of several large sun tracking mirrors that concentrate the solar energy onto the receiver placed on the top of a central tower.

The third technology uses a parabolic dish-shaped solar concentrator that concentrates the sunlight onto a receiver placed at the focal point of the dish.

The paper is organized as follows: Section 3 presents a description of the CSP under test, Section 4 shows the Matlab based model and Section 5

discusses the results obtained by the Matlab-based GUI. Conclusions end the paper.

This chapter is based on the revised version of the paper presented at the International Conference on Renewable Energies and Power Quality (ICREPQ'12) [9].

## **Description of the CSP under test**

This paper focuses on the CSP based on parabolic troughs. An Italian pilot project named Archimede [10], based on this technology, was proposed by ENEL (Italy's largest power utility) and ENEA (Italian National agency for new technologies, energy and sustainable economic development) in the South of Italy.

The CSP model proposed in this paper utilized Archimede as a reference. Sub-section A presents the components, while sub-section B describes the layout of the proposed model.

### ***Components and operation of the CSP***

The CSP under investigation is constituted by the following main components:

- linear parabolic trough-shaped mirrors, named collectors, to focus the sun's rays onto a receiver pipe (inside and coaxial with a vacuum glass pipe) running along the focal line and containing a flowing fluid;
- hydraulic circuit with molten salts that connects the field of reflectors and the storage system, including the control system for controlling the temperature of the salts and the devices for loading and unloading the salts;
- pumping systems of the salts;
- storage system consisting of two tanks with a circular section;
- electrical power station equipped with two steam turbines (high and low pressure, respectively), a molten salt steam generator, a condenser with an appropriate cooling system (water or air) and the feed water preheating system.

The reflectors concentrate the sun's rays on the receiver and the heated fluid is transported to the energy conversion system. During this step, a part of the fluid can be stored for a posterior use. Then the remaining part is utilized to produce electrical energy. The energy conversion system is

similar to that of a common fossil fuel plant utilizing a thermal steam Rankine cycle. Usually, a mineral oil is used but it is expensive and highly flammable, and therefore can lead to important problems if it leaks at the operating temperature (290-390°C). For these reasons, a fluid constituted by a mixture of salts, sodium (60%) and potassium (40%) nitrate was considered; this fluid is largely used in the industry because it is chemically stable up to 600°C and causes no corrosion problems.

Moreover, the thermal storage system enables the storing of the solar energy, which can then be used when the sun is not present (during the night, in the presence of clouds and so on). This is a very important task for each solar plant. In fact, the unpredictability of energy production is the main disadvantage of solar plants, and is usually pointed out by the detractors of solar energy plants. Thermal storage enables decoupling thermal energy collecting from electrical energy production, i.e. it is not necessary to produce and to use the electrical energy just when the thermal energy is collected. In this way, it is possible to have a more efficient operation of the electrical generator, eliminating the stops due to cloudiness and making the system more compatible with the demands of the electricity grid. Fig. 1, from [10], reports a simplified scheme of the CSP. Three circuits are present:

1. the primary loop, devoted to the harvesting, distribution and storage of the solar thermal energy;
2. the secondary loop, where the thermal energy stored in the hot tank is utilized in the steam generator;
3. the thermal cycle, where thermal energy is transformed into electrical energy.

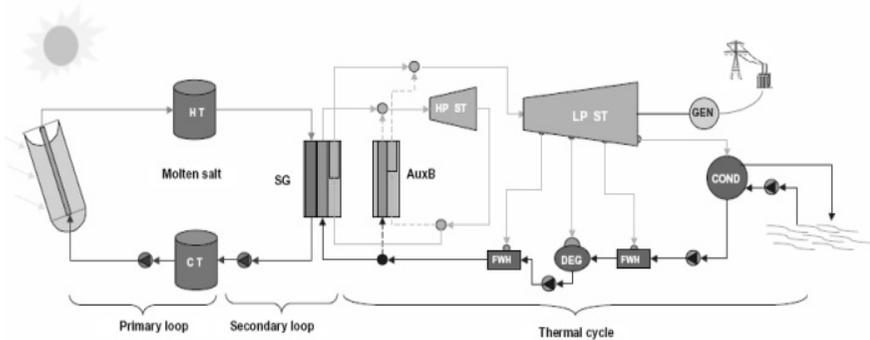


Fig. 1. CSP under investigation

The operation principle of the CSP under investigation is the following.

When direct solar radiation is present, the thermal fluid, taken from the cold tank at a temperature of 290°C, flows into the receivers and heats up until 550°C. Then, it is pumped into the hot tank, where it is stored. The flow of molten salts into the primary circuit is adjusted with respect to the solar radiation in order to maintain the input temperature of the hot tank constant. As the molten salts have a high temperature of solidification (238°C), it is necessary to maintain a minimum flow capacity when the solar radiation is not present or to provide heating systems of the pipes to avoid the fluid temperature falling below that point.

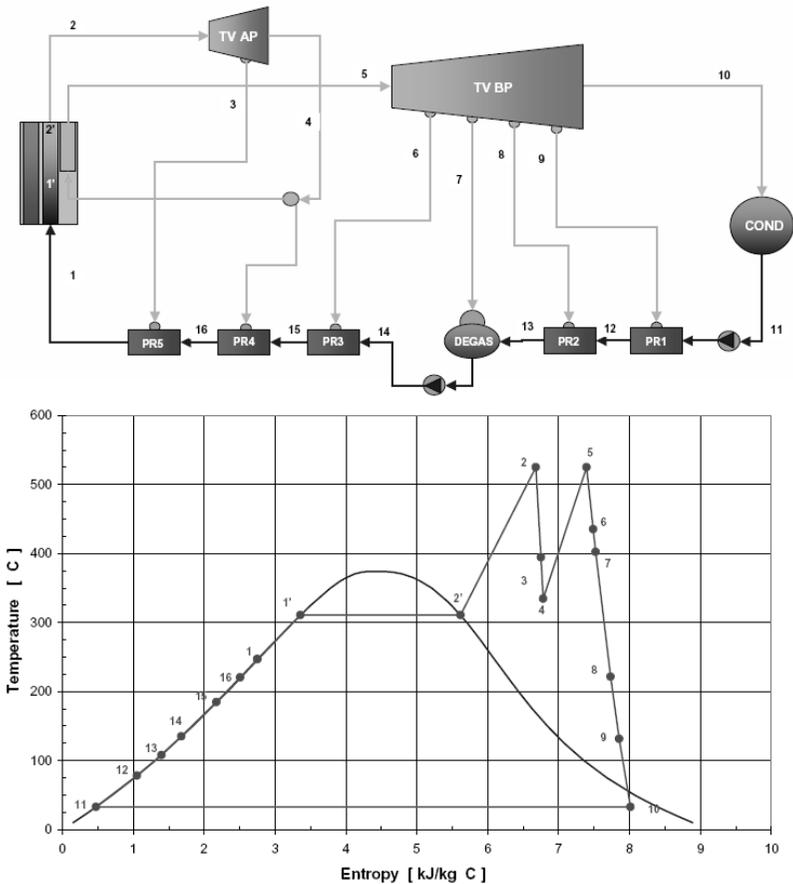


Fig. 2. Thermal cycle (a) and T-E diagram (b).

When electrical energy is requested, the salts stored in the hot tank are pumped into the heat exchanger, where steam at high pressure and temperature is produced. Then, the molten salts are collected in the cold tank. As already said, the thermal cycle is similar to that of a common fossil fuel power station. Two turbines for high and low pressure are present (Fig. 1); the superheated steam has a temperature of 525°C and a pressure of 120 bar when it expands through the high pressure turbine. The electrical rated power of the CSP is 40 MW, while the efficiency of the thermal cycle is equal to 42.3% in rated power conditions. A detailed representation of the thermal cycle is reported in Fig. 2a, while Fig. 2b represents the Temperature-Entropy diagram [10]. The numeration in the upper figure allows the path of the fluid to be followed, while the lower figure highlights the temperature value at each corresponding step.

### *Layout of the collectors and characteristic parameters*

Fig. 3, from [10], reports the layout of the modelled CSP. It can be observed that the thermal power station (turbines, steam generator, condenser and tanks) is in a central position, while the solar field is constituted by three areas, two of them containing 33 Solar Collector Assembly (SCA) and third one containing 70 SCA. The SCA are parallel-connected to each other. Each SCA of each area is constituted by six series-connected collectors and each collector is 100m long and has a span of 5.76m. Therefore, one SCA is 600m long while the distance between two SCA is equal to 2 times the span of a collector. Table 1 reports the main parameters of the CSP.

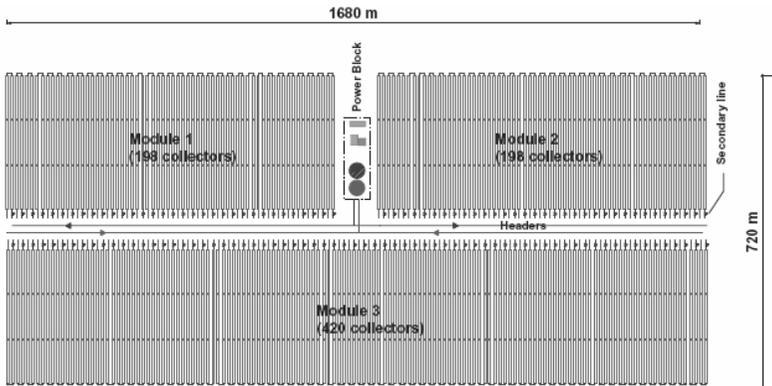


Fig. 3. Layout of the CSP (N-S orientation).

## MATLAB based model of the CSP

Unlike a PV plant for which all the three components of solar radiation (direct, diffuse and reflected) are useful for energy production, the CSP utilizes the direct component only. For this aim, it is necessary to know the DNI for the installation site. In this model, we consider that the CSP is located in Bari, a city of the South of Italy different from the installation site of ENEA's project. The values of DNI for Bari are not available, but in Mediterranean countries the values of the DNI are similar to the values of Global Horizontal Irradiation (GHI), as reported in Fig. 4; then, GHI values are used for this paper. As the collectors can rotate on a single axis, it is necessary to define the orientation of their axes, North-South (N-S) or East-West (E-W). Fig 5 reports the values of the average daily radiation for the 12 months of a year (DNI equal to 1731 kWh/m<sup>2</sup>/year). It can be noted that the radiation on the collector is larger for the N-S orientation than for E-W. Table 2 compares several parameters for both the N-S and E-W orientations, considering a 40MWe rated power CSP. It results that the number of collectors needed, as well as the area of the solar field and the occupied land, is smaller for the N-S orientation than for E-W. Then, the N-S orientation is considered hereafter.

**Table I: Parameters of the CSP**

Number of collectors	816
Area of each collector	3317.76 m <sup>2</sup>
Total collector area	45*10 <sup>4</sup> m <sup>2</sup>
Distance between collectors	11.5 m
Peak power of the solar field (with a radiation of 900W/m <sup>2</sup> and an efficiency of the collector equal to 0.79)	321 MWt
Solar field area	900,000 m <sup>2</sup>
Temperature of the hot tank	550 °C
Temperature of the cold tank	290 °C
Storage capacity	3000 MWh
Rated electrical power	40 MWe
Thermo-electrical efficiency in rated electrical power	0.423
Produced energy for year	413 GWh/year
Load factor (ratio between produced energy and energy obtained if the CSP worked in the rated conditions during the whole year)	0.48
Mean collector efficiency for one year (depending on the annual direct radiation)	0.67

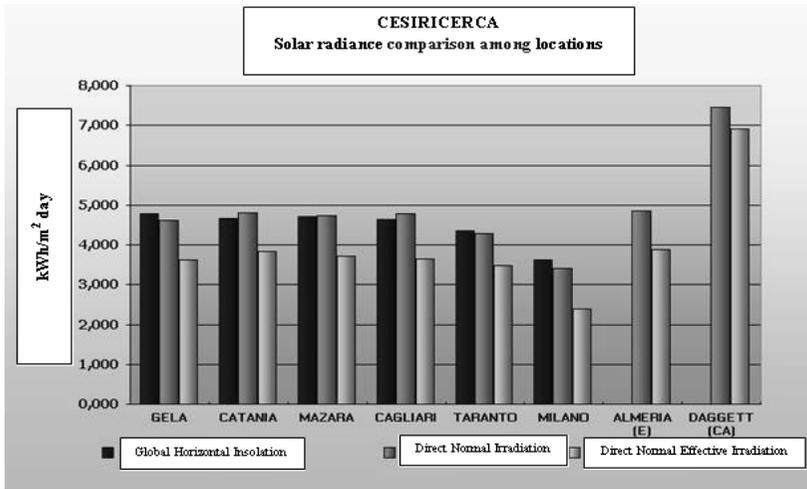


Fig. 4. Comparison between GHI and DNI

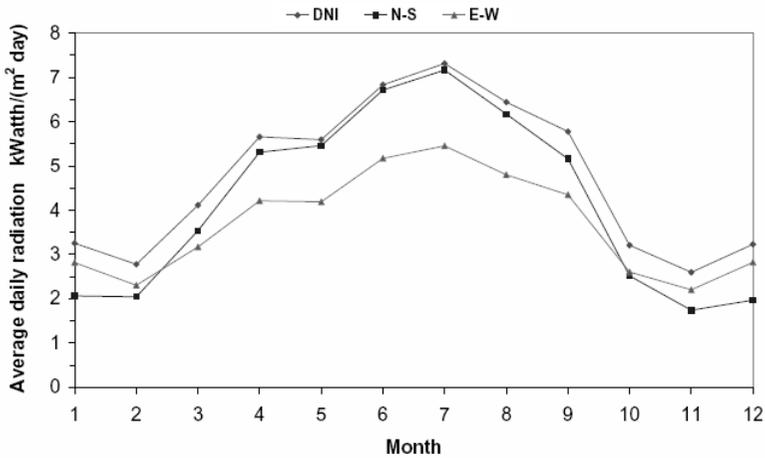


Fig. 5. Solar radiation for the site of Gela (1993, CESI).

**Table II: Comparison between N-S and E-W orientations for CSP of 40 MW<sub>e</sub> rated power**

	N-S	E-W
DNI [kWh/(m <sup>2</sup> ·year)]	1731	
Radiation on the collector [kWh/(m <sup>2</sup> ·year)]	1520	1344
Relative radiation (% DNI)	88%	78%
Number of collectors	816	1,008
Area of the solar field [m <sup>2</sup> ]	451,215	557,384
Occupied land [m <sup>2</sup> ]	900,000	1,110,000

As the secondary loop and the thermal cycle of Fig. 1 represent the standard operation of a common fossil fuel power station utilizing a Rankine cycle, the model proposed in this paper is limited to the primary loop only, i.e. the thermodynamic system. Fig. 6 reports the proposed algorithm for modelling the primary loop of Fig. 1. It can be noted that two sets of input data are necessary. The former one concerns the installation site: latitude, altitude, climate conditions, available surface, shadings and so on. The latter one is constituted by the geometric dimensions of each collector, number of collectors (depending on the desired electrical power), number of SCAs, typology of fluid, and so on. The first set of input data allows the DNI to be evaluated while the second one allows the layout of the solar field to be defined. Finally, a mathematical model of the thermodynamic system is obtained, considering the fluid starting from the cold tank and arriving to the hot tank, flowing through the network of receivers.

As previously explained, the fluid considered in this paper is constituted by a binary mixture of salts, sodium (60%) and potassium (40%) nitrate. Some physical parameters of this mixture, needed for evaluating the Nusselt number (see later eq. (12)), were obtained by linear regression based on literature data. They are defined in the following equations ( $T_{\text{salts}}$  is the temperature of the molten salts), while Fig. 7 is a diagrammed representation.

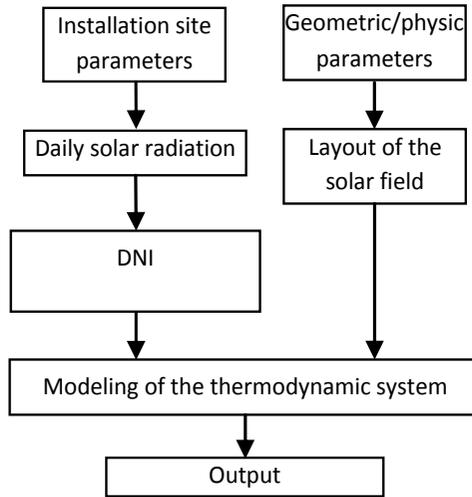


Fig. 6. Modelling steps of primary loop of Fig. 2

- Dynamic viscosity:

$$\mu = \frac{(425,239,400 \cdot T_{salts}^{-2,945})}{1000} \quad (1)$$

- Density:

$$\rho = -0.657 \cdot T_{salts} + 2317.2 \quad (2)$$

- Kinematic viscosity:

$$\nu = \frac{\mu}{\rho} \quad (3)$$

- Specific heat:

$$c_{p_s} = 1443 + 0.172 \cdot (T_{salts} - 273.15) \quad (4)$$

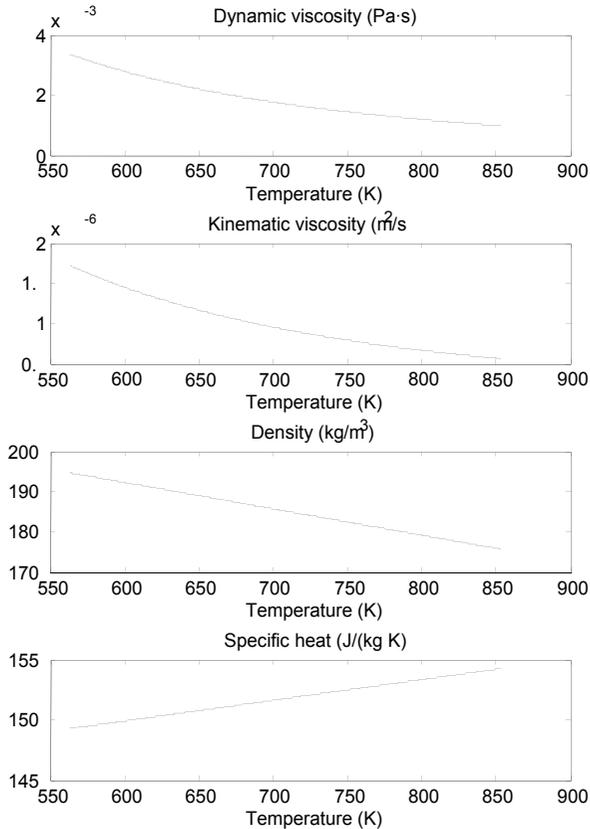


Fig. 7. Some physical parameters of the mixture of salts used for the model.

The output data of the model are the thermal efficiency, the thermal power and the final fluid temperature (corresponding to the fluid stored in the hot tank). As these parameters depend strongly on the thermal losses, it is necessary to evaluate all of them first. In the following, all the considerations will regard a single receiver, also named absorber. Thermal losses of the absorber can be classified as [11]:

1. losses from the receiver to the low-pressure zone inside the glass pipe through radiation,  $Q_{ab,r}$ , and conduction and convection with the residual gas,  $Q_{ab,c}$ ;

2. losses from the receiver to the external environment due to the metal bellows needed for thermal expansion,  $Q_b$  ;
3. losses from the glass pipe to the environment due to radiation,  $Q_{g,r}$  , and to convection,  $Q_{g,c}$  .

The several contributions can be evaluated as follows [11]:

$$Q_{ab,r} = \frac{\sigma \cdot (T_{ab}^4 - T_g^4)}{\frac{1}{\varepsilon_{ab}} + \left( \frac{1}{\varepsilon_g} - 1 \right) \cdot \frac{r_{ab}}{r_g}} \cdot S_{ab} \quad (5)$$

where  $\sigma$  is the Stefan-Boltzman constant,  $T_{ab}$  the absorber temperature,  $T_g$  the glass temperature,  $S_{ab}$  the surface for the thermal transfer,  $r_{ab}$  the radius of the absorber pipe,  $r_g$  the radius of the glass pipe,  $\varepsilon_g$  the emissivity of the glass, and finally  $\varepsilon_{ab}$  the emissivity of the absorber, depending on the absorber temperature as  $\varepsilon_{ab} = 0.00042 \cdot T_{ab} - 0.0995$  ;

$$Q_{ab,c} = h_d \cdot (T_{ab} - T_g) \cdot S_{ab} \quad (6)$$

where  $h_d$  is the heat transfer coefficient for the low-density gas [12], depending on the air thermal conductivity, on the mean free path of the particles and on the radiuses of both the absorber and the glass pipe.

$$Q_b \approx 0.15 \cdot Q_{losses} \quad (7)$$

where  $Q_{losses}$  represents the total losses.

$$Q_{g,r} = \sigma \cdot \varepsilon_g \cdot (T_g^4 - T_{sky}^4) \cdot S_g \quad (8)$$

where  $S_g$  is the glass surface, while the sky temperature  $T_{sky}$  can be evaluated as [14]:

$$T_{sky} = (\varepsilon_{sky})^{0.25} \cdot T_a \quad (9)$$

where  $T_a$  is the dry bulb temperature, while  $\varepsilon_{sky}$  is a second-order polynomial function of the dew point ambient temperature.

Finally,

$$Q_{g,c} = h_c \cdot (T_g - T_a) \cdot S_g \quad (10)$$

where  $h_c$  is the external convection heat transfer, equal to:

$$h_c = \frac{\lambda}{2r_g \cdot N_u} \quad (11)$$

where  $\lambda$  is the air thermal conductivity and  $N_u$  is the Nusselt number, related to the Reynolds number and to the Prandtl number:

$$Nu = 0.3 + \frac{0.62 \cdot Re^{0.5} \cdot Pr^{1/3}}{1 + \left(\frac{0.4}{Pr}\right)^{2/3}} \cdot \left[1 + \left(\frac{Re}{282000}\right)^{5/8}\right]^{4/5} \quad (12)$$

Taking into account the previous losses, the thermal efficiency can be calculated as:

$$\eta = \eta_{opt} \cdot k - \frac{Q_{losses}}{I_{direct} \cdot S} \quad (13)$$

where  $\eta_{opt}$  represents the optical efficiency (fixed to 0.8, standard value),  $S$  the surface of the collector,  $I_{direct}$  the direct radiation and  $k$ , taking into account the angle error of the pointing system [14], is defined as:

$$k = \cos \vartheta + 0.000994 \cdot \vartheta - 0.00005369 \cdot \vartheta^2 \quad (14)$$

$\vartheta$  being the angle between the incident ray and the normal to the front plane of the reflector.

Finally, the thermal power,  $Q_{fluid}$ , can be calculated as:

$$Q_{fluid} = \eta \cdot I_{direct} \cdot l_A \cdot l_s \quad (15)$$

where  $l_A$  is the span of the collector and  $l_s$  is the length of the SCA.

At this point the final fluid temperature is:

$$T_U = T_I + \frac{Q_{fluid}}{G_s \cdot c_{ps}} \quad (16)$$

where  $T_I$  is the initial temperature (i.e. the fluid temperature in the cold tank),  $G_s$  the flow capacity and  $c_{ps}$  the specific heat of the molten salts. It can be noted that  $T_U$  decreases as  $G_s$  increases: in fact, the larger the flow capacity, the shorter the time necessary to pass through the receiver, and the smaller the thermal energy captured by the fluid.

## Results

After modelling the thermodynamic system, some simulations were run in Matlab in order to evaluate its performance. To this aim, several input variables were considered because, for example, the thermal performance (i.e. the final temperature of the molten salts,  $T_U$ ) depends on the length of a single collector, on its flow capacity and on the radiation. Diagrammed output variables, as already said, will be the thermal performance,  $T_U$ , the thermal power,  $Q_{fluid}$ , and the thermal efficiency,  $\eta$ .

Fig. 8a reports  $T_U = f(G_s)$  for several values of radiation. As can be seen, for a fixed value of  $I_{direct}$ ,  $T_U$  decreases as  $G_s$  increases, whereas for a fixed value of  $G_s$ ,  $T_U$  increases as  $I_{direct}$  increases. Then the correlation between  $T_U$  and  $G_s$  is opposite with respect to the correlation between  $T_U$  and  $I_{direct}$ . Fig. 8b resumes the previous considerations in a 3D diagram. Fig. 9 reports the final temperature  $T_U = f(l_s)$  for different values of flow capacity  $G_s$ . It can be noted that, for  $G_s > 3kg/s$ ,  $T_U$  increases linearly as  $l_s$  increases, whereas for  $G_s \leq 3kg/s$  the correlation between  $T_U$  and  $l_s$  is still positive but nonlinear. Fig. 9 was obtained with  $I_{direct} = 350W/m^2$ ; similar diagrams are obtained for different values of  $I_{direct}$ .

Fig. 10a diagrams the thermal power depending on the flow capacity of the molten salts, for a fixed value of  $I_{direct}$ . In this case, the relation is also linear for higher values of  $G_s$ ; otherwise, it is nonlinear. It can be noted that  $Q_{fluid}$  increases as  $G_s$  increases (for a fixed value of  $I_{direct}$ ) and as  $I_{direct}$  increases (for a fixed value of  $G_s$ ). Fig. 10b contains all this information in a single 3D diagram.