# OPTIMAL ECONOMIC DISPATCH FOR CARBON CAPTURE POWER PLANTS USING CHAOS-ENHANCED CUCKOO SEARCH OPTIMIZATION ALGORITHM

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Dedicated to

My mother, **Sahra Iidan Abdilahi**, whose sacrifice;
My father, **Mohamed Abdilahi Uurcade**, whose dream;
My **Brothers and great sister**, whose love, support and encouragement;
And
My friends whose friendship;
Lead to achieve my doctoral degree

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# ABSTRACT

Accelerated global demand for low carbon operation of power systems have stimulated interest in Low Carbon Technologies (LCTs). The increased deployment of LCTs within power systems is fundamental to the emission abatement of power system. Carbon Capture Power Plant (CCPP) technology has a good potential for future low carbon emission. Existing Economic Dispatch (ED) formulations do not consider the flexibly-operated CCPPs. Flexible operation of Carbon Capture and Storage (CCS) units transforms conventional power plants in such a way that emission output and power output could be separately controlled. The resulting CCPPs have to be optimized in order to take advantage of the incentives available in both power and carbon markets. This thesis proposes an improved mathematical modelling for flexible operation of CCPPs. The developed work possesses simple and practical variables to appropriately model the flexible operation control of the CCPPs. Using this proposed model a new emission-oriented ED formulation is developed. With this new formulation, the thesis also proposes the concept of decoupling the emission and economic outputs and then quantifies its significance for power system operations. In addition to that, a new Metaheuristic Optimization Technique (MOT) named as Chaos-Enhanced Cuckoo Search Optimization Algorithm (CECSOA) has been developed to improve global optimum result for ED problem. The algorithm has been tested using standard test systems with varying degrees of complexity. The results proved that the CECSOA is superior to the existing techniques in terms of ability to obtain global optimal points and the stability of the solutions obtained. Simulation results also showed the possibility of $1.09 million of annual operational cost savings based on a practical power system located in the Greek island of Crete by applying this methodology in comparison with conventional techniques such as Genetic Algorithm. Further results showed that for a carbon price of 20 $/tCO_2$ and a 60% of system capacity utilization, total emission of a power system is reduced by 10.90% as compared to a “business-as-usual” scenario. In terms of optimal ED for CCPPs, results showed that for carbon prices as low as (~ 8 – 10 $/tCO_2$), it is economically viable to operate a post-combustion CCS unit.

# ABSTRAK

Permintaan global secara mendadak bagi operasi karbon rendah dalam sistem kuasa telah menarik minat kepada Teknologi Karbon Rendah (LCT). Peningkatan pelaksanaan LCTs dalam sistem kuasa adalah asas kepada pengurangan pelepasan daripada sistem kuasa. Loji Kuasa Penangkapan Karbon (CCPPs) adalah teknologi yang berpotensi untuk pelepasan karbon rendah pada masa depan. Formulasi Penghantaran Ekonomi (ED) yang sedia ada tidak mengambil kira CCPP yang beroperasi secara fleksibel. Operasi Tangkap dan Simpan Karbon (CCS) yang fleksibel mengubah loji kuasa yang lazim di mana keluaran pelepasan dan penjanaan kuasa dapat dikawal secara berasingan. CCPP yang terhasil perlu diperkukuhkan untuk mengambil peluang daripada insentif sedia ada di pasaran kuasa dan karbon. Tesis ini mencadangkan satu model matematik yang dioptimumkan untuk operasi CCPP yang fleksibel. Kerja yang dibangunkan mempunyai pembolehubah yang mudah dan praktikal bagi mereka model kawalan operasi CCPP yang fleksibel. Dengan menggunakan model yang dicadangkan ini, satu formulasi penghantaran ekonomi baru yang berorientasikan pelepasan telah dibangunkan. Dengan formula baru ini, projek ini juga mencadangkan konsep pemisahan antara pelepasan dan keluaran ekonomi dan seterusnya mengukur keberkesanannya terhadap operasi sistem kuasa. Selain itu, satu Teknik Pengoptimuman Metaheuristik (MOT) baharu yang dikenali sebagai Algoritma Pengoptimuman Carian Cuckoo Berkecamuk Tertambah (CECSOA) telah digunakan bagi mencari keputusan yang optimum untuk masalah penghantaran ekonomi. Algoritma ini telah diuji menggunakan beberapa sistem ujian piawai dengan pelbagai peringkat kerumitan. Keputusan simulasi menunjukkan bahawa CECSOA adalah jauh lebih baik berbanding dangan teknik yang sedia ada berdasarkan kualiti keputusan yang diperolehi. Keputusan tambahan juga menunjukkan penjimatan kos operasi tahunan sebanyak $1.09 juta berdasarkan sistem kuasa praktikal yang terletak di Crete, kepulauan Greek dengan metod ini berbanding dengan Algoritma Genetik. Keputusan seterusnya menunjukkan pada harga 20 $/tCO_2$ dan sistem beroperasi pada kapasiti 60%, jumlah pelepasan berkurang sebanya 10.90% berbanding dangan senario "*business-as-usual*". Dari segi optimum ED untuk CCPP, keputusan menunjukkan pada harga karbon serendah (~8-10 $/tCO_2$) bagi operasi unit pasca-pembakaran CCS adalah secara ekonomikal berdaya maju dangan ekonomikal.

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| | | |
|---|---|---|
| ABC | - | Artificial Bees Colony |
| AU$ | - | Australian Dollar |
| BA | - | Bat Algorithm |
| BAU | - | Business As Usual |
| BGA | - | Binary Genetic Algorithm |
| CCPP | - | Carbon Capture Power Plant |
| CCS | - | Carbon Capture and Storage |
| CECSOA | - | Chaos-Enhanced Cuckoo Search Optimization Algorithm |
| CEED | - | Combined Emission Economic Dispatch |
| CHM | - | Constraint Handling Mechanism |
| CM | - | Chaotic Maps |
| $CO_2$ | - | Carbon Dioxide |
| COP | - | Conference of Parties |
| CP | - | Carbon Price |
| CS | - | Cuckoo Search |
| CT | - | Carbon Tax |
| DE | - | Differential Evolution |
| DEED | - | Decoupled Emission Economic Dispatch |
| EC | - | Emission Cost |
| ED | - | Economic Dispatch |
| EP | - | Evolutionary Programming |
| EU | - | European Union |
| FA | - | Firefly Algorithm |
| FC | - | Fuel Cost |
| GA | - | Genetic Algorithm |

| | | |
|---|---|---|
| GD | - | Gaussian Distribution |
| GHG | - | Greenhouse Gas |
| IEA | | International Energy Agency |
| IEEE | - | Institute of Electrical and Electronic Engineering |
| IPCC | - | Intergovernmental Panel on Climate Change |
| LF | - | Levy Flight |
| LHS | - | Latin Hypercube Sampling |
| LI | - | Lambda Iteration |
| Mtpa | - | Million Tonnes Per Annum |
| MEA | - | Mono-Ethanol-Amine |
| MOT | - | Metaheuristic Optimization Technique |
| $NO_X$ | - | Nitrogen Oxides |
| NP | - | Non-capture power Plant |
| OC | - | Overall (system) Cost |
| Pdt | | Total System Demand |
| PF | - | Penalty Factor |
| PSO | - | Particle Swarm Optimization |
| RGA | - | Real-coded Genetic Algorithm |
| RW | - | Random Walk |
| SCU | - | System Capacity Utilization |
| SCS | - | Standard Cuckoo Search |
| SI | - | Swarm Intelligence |
| SR | - | Success Rate |
| STD | - | Standard Deviation |
| UK | - | United Kingdom |
| UN | - | United Nations |
| US | - | United States |
| WECS | - | Wind Energy Conversion Systems |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $a_C$ | - | Capture rate of the scrubber |
| $a_i$ , $b_i$ , $c_i$ | - | Coefficients for fuel cost characteristics of the plants |
| $\beta$ | - | Levy flight exponent |
| $C_F$ | - | Fuel cost of the non-capture plants |
| $C_E$ | - | Emission cost of the non-capture plants |
| $C_{FC}$ | - | Fuel cost of the capture plants |
| $C_{EC}$ | - | Emission cost of the capture plants |
| $C_{OO}$ | - | Overall operating cost |
| $CP$ | - | Carbon price |
| $d$ | - | Index counter for non-capture plants |
| $d_i$ , $e_i$ | - | Valve point loading coefficients |
| $E_C$ | - | Captured emission |
| $\varepsilon$ | - | Uniformly distributed random number |
| $e_E$ | - | Emission intensity |
| $E_G$ | - | Gross emission |
| $E_N$ | - | Net emission |
| $ef$ | - | Emission factor |
| $EM$ | - | $CO_2$ emission function |
| $f_i$ , $g_i$ , $h_i$ | - | Fuel consumption coefficients (emission coefficients) |
| $H(u)$ | - | Heaviside function controlled by a switching |

| | | |
|---|---|---|
| | | parameter $P_a$ |
| $i$ | - | Index counter for individuals within the population |
| $k$ | - | Index counter for CCPPs |
| $Levy(\beta)$ | - | Levy flight function |
| $\lambda$ | - | Penalty factor for amplifying the generator output error |
| $N_{CP}$ | - | Number of capture plants |
| $N_{NP}$ | - | Number of none-capture plants |
| $N_D$ | - | Number of population |
| $N_X$ | - | Number of decision variables |
| $P_a$ | - | Switching parameter |
| $P_{BP}$ | - | Basic penalty of the CCPP |
| $P_{CP}$ | - | Capacity penalty of the gross power output for the CCPP |
| $P_D$ | - | Total system demand |
| $P_G$ | - | Gross output power of the CCPP (scheduled) |
| $P_i$ | - | Scheduled power of the non-capture plant |
| $P_L$ | - | Power loss |
| $P_N$ | - | Net output power of the CCPP |
| $P_{OP}$ | - | Operating penalty power of the CCPP |
| $P^{max}$ | - | Maximum stable generation |
| $P^{min}$ | - | Minimum stable generation |
| $p(z)$ | - | Penalty term for penalizing infeasible candidate solutions |
| $t$ | - | Index counter for iterations of the algorithm |
| $w_{CC}$ | - | Amount of energy consumed by the CCS for every $CO_2$ treated |
| $x_{i,j}$ | - | Population of nests |

| | | |
|---|---|---|
| $x_i^{new}$ | - | New candidate solutions |
| $x_m$ and $x_n$ | - | Two different solutions $(m \text{ and } n)$ selected randomly by permutation |
| $\gamma_C$ | - | Normalized rate of the treating ability of the stripper and the compressor |
| $y(t)$ | - | Value of the chaotic map at each iteration $t$ |
| $y_0$ | - | Initial value of the chaotic maps |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

The Intergovernmental Panel on Climate Change (IPCC) projections indicate that avoiding the most serious impacts on climate change demands to limit the increase in global average temperature at 2° C. This sets a global "carbon budget" that has to be met and puts constraint on the global fossil fuel use because of their inherent carbon dioxide ($CO_2$) emission. Because of this carbon budget, the electricity industry, which accounts more than 42% [1] of the global $CO_2$ emissions, is subjected to shift to a low-carbon future. To put the low-carbon future into perspective, for instance, in the European Union (EU) alone the power sector emission reductions "are projected to achieve reductions of 54% - 68% by 2030 and 93% - 99% by 2050 compared to 1990" levels [2]. The transitions to such low carbon power systems, in global scale, demands a shift to low-carbon technologies such as renewable technologies, nuclear power and fossil fuel generators with carbon capture and storage (CCS) [3]. This underscores the significant impact of climate change measures on the power generation system.

Concurrently, certain regulatory policies are advocated to be implemented globally in order to ease and accelerate the deployment of the low carbon technologies within the power generation. To this end, "many countries have introduced or are considering the introduction of some form of carbon price, typically through an emissions-trading scheme, whereby overall emissions are capped and the price that must be paid to emit a tonne of $CO_2$ is set by the market, or through a fixed-rate carbon tax" [4]. These measures put pressure on the heavy carbon emitters to curb their emissions.

With these concurrent paradigms occurring simultaneously that drive modernisation of current grid configuration, system operational routines need to be revisited in a way that capitalizes the new low carbon technologies at the best interest of the grid. For example, the carbon pricing instruments bring in external costs to the electricity generation while the low carbon technologies bring in new forms of system operation and strategies. In line with this, this research work aims to bridge the knowledge between optimal operation of power systems, carbon capture and storage (CCS), and power system markets with consideration of system economics and carbon mitigation policies.

The optimal setting of output levels of available generators can play a vital role in the economics of any power system. A proper schedule of available generating units may save millions of dollars per year in production cost within large-scale power systems [5, 6]. For any power system market, the optimization of economic dispatch (ED) is of economic value to the network operator. The economic dispatch is a relevant procedure in the operation of a power system [7]. ED determines the optimal real power settings of generating units. It is normally formulated as a mathematical optimization problem whose objective is to minimize the total operations cost of dispatch solutions for a specified load at a given time whilst satisfying system constraints [8].

Because of the ED's nature as a typical practical power system optimization problem, adopting a state-of-the-art solution-oriented technique in the field of ED has two advantages over the usability of the conventional techniques. Firstly, metaheuristic optimization techniques (MOTs) make possible to achieve better problem modelling that reduce assumptions related to problem formulations in terms of nonlinearity. Secondly, MOTs have better ability to obtain optimal solutions as compared with a conventional technique. Both of these issues would allow the power utilities to operate the least cost possible leading to significant cost savings over the years.

Metaheuristic optimization techniques (MOTs) are iterative techniques that can search not only local optimal solutions but also a global optimal solution depending on problem domain and execution time limit. They are general-purpose searching techniques based on principles inspired from the genetic and evolution mechanisms observed in natural systems and populations of living species and organisms [9]. These methods have the advantage of searching the solution space more thoroughly. The main difficulty is their sensitivity to the choice of parameters. Within the ED solution approach, MOTs are gradient-free methods with general purpose ability. However, they have randomness. For a practical problem, like ED, the MOTs should be modified accordingly so that they are suitable to solve ED problem with, and their randomness should be addressed.

## 1.2 Problem Statement

The total emission output in the modern power generation system has created global concern. With the world's first carbon capture power plant of a utility-scale coming online in 2014, many of these types of plants are expected to be deployed in the near future for many different power systems throughout the world. The deployment of CCPPs in the power system bring in a new complexity to the system operations routines. In that regard, the system operations computational tools should be modified with respect to the changes of the technology mix of the system. With the introduction of a carbon market, the resulting CCPPs have to be optimized in order to take advantage of the incentives available in both the power and carbon markets. Thus, the optimal ED problem is reformulated by developing the decoupled emission economic dispatch problem formulation that aims to accommodate and simulate the expected changes within the system dispatch when CCPPs are considered.

As ED problem is formulated as a mathematical optimization problem, efficient optimization techniques must be designed for global optimal search. Metaheuristic optimization techniques applied in ED problems typically adopt learning mechanisms to avoid being trapped at a local optimum. But they also suffer from potential problems including divergence, parameter selection, termination condition and variance in outcomes. In particular, the lack of robustness in the optimal solutions was evident within the results obtained by the proposed algorithms when applied to nonlinear, nonconvex and highly multimodal ED problems. Optimal results which are not robust enough are not practical in reality within the practical power system context. These problems are addressed in this thesis by adopting a robust-oriented Chaos-Enhanced Cuckoo Search Optimization Algorithm (CECSOA).

## 1.3 Objectives

The objectives of the research are:

i. To develop a new emission economic dispatch formulation based on CCPP adoption within the power generation portfolio.

ii. To develop a new constraint handling mechanism (CHM) for metaheuristic optimization techniques solving the ED problems.

iii. To develop a novel robust-oriented Chaos-Enhanced Cuckoo Search Optimization Algorithm (CECSOA) for result robustness using the developed CHM for the dual purpose of local searching and equality constraints fulfilment.

iv. To improve the existing performance values achieved by the latest optimization algorithms when implemented in solving the ED problems with valve point effects using the developed CECSOA.

## 1.4 Scope

The scope of this research covers the following:

i. In terms of the various different types of low carbon technologies that are considered for power generation decarbonization pathways, this thesis focuses the CCS technology. Other technologies such as the wind and solar are not considered in this thesis.

ii. While there are various established CCS technologies globally, the study does not aim to consider comprehensive options of CCS technologies. Instead, the study focuses, in terms of CCS's integration pattern with the conventional power plant, on the post-combustion technologies. Post combustion technologies are the most mature technologies and already being deployed at a commercial scale, with examples such as the Boundary Dam Project [10] and the Toshiba pilot facility at Fukuoka [11, 12]. In terms of $CO_2$ separation technology considered, the thesis considers the amine-based types. Other technologies such as the use of membrane is ignored in this thesis.

iii. This work concentrates on the operational time-frame of the power system formulations. The time range of these operational tools involves hourly dispatch calculations of the operations of the network. The thesis also considers the static ED problem formulations which provides a snap-shot of the optimal settings of the generators at specific hourly interval.

iv. The research focuses on the possible improvement for the stability of the solutions obtained by the algorithm as opposed to other research paradigms such as the computational time.

v. IEEE 30 bus test system, the power system of Greek Island of Crete and algorithmic-oriented power system test systems (systems with 13 units and 40 units) with different levels of complexity are utilized to test the algorithms developed within this thesis.

## 1.5 Significance of the Research

The significance of this research can be viewed from different perspectives that includes but not limited to:

i. In this new era of climate-controlled power generation systems, emission economic dispatch formulations can be re-formulated to contextualize the operations of the power system network. This thesis presents the opportunity to independently control the economic and emission outputs of the generation fleet by flexibly operating the CCS technologies retrofitted at the existing facilities. Consequently, net power output to the grid and emission output to the atmosphere can be decoupled as two independent variables that can be controlled by system operators in a way that best serves the grid under the existing regulations or market opportunities. To achieve this, this work attempts to model power system formulations that can represent the operational characteristics of the CCPP units within the power system operation calculations. These new formulations are then integrated within the existing ED problem formulations.

ii. The work of this thesis is expected to be crucially useful worldwide, as different countries are adopting differing prices according to the respective socio-political and economic situations. For example, Australia adopted a CT price of 24 $/t$CO_2$ [13] while China's Guangdong province adopted a CT price of 95 $/t$CO_2$ [14]. Many other high income countries are looking at ways to adopt similar carbon pricing instruments to force lowering the $CO_2$ emissions in the foreseeable future such as the case in South Africa [15] and Russia [16].

iii. Currently, the incorporation of the CCPP models within the power system is still being researched world-wide. These models will allow the simulation of the facilities within the typical power system operations calculations. System planners will therefore use the developed tools to carry out their operations calculations without the need to mathematically and rigorously model the plant characteristics.

### 1.6 Thesis Organisation

The thesis comprises of five chapters. The first chapter provides the general overview of the study by firstly giving the background, problem statement and the research objectives. It also provides the research scope and the significance of the research.

The second chapter is designed in order to provide a comprehensive critical literature review of the different aspects. It is divided into two major parts. The first part focuses on the literature related to the different aspects of the power systems. The second part focuses on the improvement of optimization techniques adopted in solving the economic dispatch problems.

The third Chapter defines the methodology of the research. Similar to the styles of the previous Chapters, the development of the power system formulations are firstly presented, followed by the description of the proposed optimization technique. Chapter 4 presents the results and discussion. Finally, the conclusions and further recommendations of the study are provided in Chapter 5.

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