

**MULTI-STAGE FLEXIBLE EXPANSION
CO-PLANNING UNDER UNCERTAINTIES IN A
COMBINED ELECTRICITY AND GAS
MARKET**

JING QIU

B.E.

M.Sc.

*A thesis submitted in partial fulfillment
of the requirements for the degree of*

Doctor of Philosophy



The UNIVERSITY
of NEWCASTLE
AUSTRALIA

June, 2014

DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying subject to the provisions of the Copyright Act 1968.

I hereby certify that the work embodied in this thesis contains published chapters/scholarly work of which I am a joint author. I have included as part of the thesis a written statement, endorsed by my supervisor, attesting to my contribution to the joint publications/scholarly work.

Author:

Jing Qiu

June, 2014

Approved by Principle Supervisor:

Prof. Zhao Yang Dong

June, 2014

To all my family

ACKNOWLEDGEMENTS

My Ph.D. research experience in Australia was like an amazing journey. There were plenty of wonderful and memorable stories along the journey. Every day in the journey was full of happiness, surprise and achievement. This thesis becomes an important milestone in my life, marking the completion of my Ph.D. study journey and the new start of my academic career. I would like to take this precious chance to express my deepest gratitude to those who helped and supported me during my research.

Firstly, I am truly grateful to my principle supervisor, Prof. ZhaoYang Dong. Meeting him has totally changed my entire life. It is the luckiest thing to work under his supervision. His character, wisdom and leadership have positively influenced my personal development. His continuous help, support, and guidance have been very helpful for my research. Meanwhile, I also deeply thank my co-supervisor, Prof. Yusheng Xue, from the State Grid Electric Power Research Institute, China. Prof. Xue has helped and taught me a lot for my research with his vast experience in both research and engineering practices. Working with him was also a very happy experience and with lots of gains.

Secondly, I also appreciate my colleagues, Dr. Junhua Zhao, Dr. Ke Meng, Dr. Yan Xu, Dr. Fengji Luo, Mr. Yu Zheng, and Dr. Yingying Chen. I had the pleasure of working with them. Their help and contribution are essential parts for the completion of this thesis.

Thirdly, I express many thanks to the Australian federal government, the University of Queensland and the University of Newcastle. The commonwealth supported full scholarships, International Postgraduate Research Scholarship (IPRS), Australian Postgraduate Award (APA) and University of Queensland Centennial scholarship (UQCent) provided great financial supports for my study in Australia.

Last but not least, I would like to thank my family, especially my parents and grandparents. Their love and support is a solid base when I am pursuing my dream. My special thanks go to

my dear wife, Huiqiao Tian. Her sacrifice and support is the strongest motive for me to strive for goals.

TABLE OF CONTENTS

1. INTRODUCTION.....	1
1.1 POWER SYSTEM PLANNING	1
1.1.1 Generation Planning.....	3
1.1.2 Transmission Planning.....	4
1.2 RELIABILITY CRITERION FOR POWER SYSTEM PLANNING	4
1.2.1 Adequacy	5
1.2.2 Security	6
1.3 POWER SYSTEM PLANNING IN A NEW ENVIRONMENT	7
1.4 FUEL SUPPLY, POWER GENERATION AND TRANSMISSION.....	9
1.5 STATE-OF-THE-ART	11
1.6 RESEARCH SIGNIFICANCE.....	12
1.7 RESEARCH PROBLEMS	13
1.8 CONTRIBUTION OF THIS RESEARCH.....	14
1.9 THESIS OUTLINE	17
2. LITERATURE REVIEW	21
2.1 POWER SYSTEM PLANNING	21
2.1.1 Typical Planning Models	21
2.1.2 Uncertainties	25
2.1.3 Reliability/Security	36
2.1.4 Deregulated Electricity Market.....	42
2.1.5 Planning for Integrating Renewable Energy	44
2.1.6 Coordinated Generation and Transmission Planning.....	45
2.1.7 Planning with Other Considerations	47
2.1.8 Outline of Existing Research Works	50
2.2 NATURAL GAS NETWORK MODELLING	51
2.2.1 Fundamentals in Gas Network.....	51
2.2.2 Gas Flow Modelling	52
2.2.3 Compressor Station Modelling	54
2.2.4 Linepack Modelling	55
2.2.5 Linear Gas Flow Modelling in Markets.....	56
2.3 JOINT PLANNING OF GAS AND POWER SYSTEMS	59
2.3.1 Background.....	59
2.3.2 Works on Integrated Natural Gas and Power Systems.....	62
2.4 AUSTRALIA'S GAS AND ELECTRICITY MARKETS.....	65
2.4.1 Australia's NEM	65
2.4.2 Australia' Gas Market	67
2.5 CONCLUSION.....	70
3. GENERALIZED RELIABILITY FOR INTEGRATED GAS AND POWER	

SYSTEMS	71
3.1 INTRODUCTION	71
3.2 NATURAL GAS MODELS	73
3.2.1 Gas Market	73
3.2.2 Gas Flow Equations.....	73
3.2.3 Compressors	74
3.2.4 Underground Storage.....	74
3.3 FORMULATION OF THE EXPANSION CO-PLANNING.....	75
3.3.1 Overview of the Expansion Planning Model.....	75
3.3.2 Generalized Working Condition Model.....	78
3.3.3 State Model of Gas Storage.....	80
3.3.4 EENS Calculation.....	81
3.3.5 Load.....	83
3.4 CASE STUDIES	83
3.5 CONCLUSION	92
4. PLANNING IN A COMBINED ENERGY MARKET CONSIDERING MARKET TIMELINE MISMATCH.....	95
4.1 INTRODUCTION	95
4.2 NATURAL GAS SYSTEM MODEL	96
4.2.1 Overview of the Gas Network Model.....	96
4.2.2 Linepack Equations	97
4.2.3 Flow Equation	98
4.2.4 Compressor Station Equation	98
4.2.5 Interaction between Gas and Electricity.....	99
4.3 EXPANSION CO-PLANNING FORMULATION.....	100
4.3.1 Expansion Co-planning Model.....	102
4.3.2 Market Uncertainties	104
4.3.3 System Reliability	105
4.3.4 Solution Method.....	105
4.4 CASE STUDIES	107
4.4.1 Experiment Setting.....	107
4.4.2 Three-bus Gas and Two-bus Power System	108
4.4.3 The Victorian Gas and Electricity Networks.....	111
4.5 CONCLUSION	117
5. FLEXIBILITY OF THE PROPOSED PLAN.....	119
5.1 INTRODUCTION.....	119
5.2 NATURAL GAS NETWORKS.....	122
5.3 PROPOSE FLEXIBLE CO-PLANNING MODEL.....	123
5.3.1 Formulation of the Flexible Co-planning Model.....	124
5.3.2 The Stochastic Models	129
5.3.3 Solution Methods	130
5.4 CASE STUDIES	132
5.4.1 Experiment Setting.....	132

5.4.2	Computational Efficiency	133
5.4.3	Comparison and Discussion.....	134
5.5	CONCLUSION.....	140
6.	ENERGY NETWORK'S VULNERABILITY TO EXTREME EVENTS.....	143
6.1	INTRODUCTION	143
6.2	ECONOMIC ADJUSTMENT INDEX.....	145
6.2.1	Conventional Risk Value Calculation	145
6.2.2	Economic Adjustment Index and Adjusted Risk Value.....	146
6.3	UNCERTAINTY MODELING	147
6.3.1	Wind Power Uncertainty Modeling	147
6.3.2	Load Uncertainty Modeling.....	149
6.3.3	Component Availability Modeling.....	149
6.4	PROBABILISTIC PLANNING WITH ECONOMIC ADJUSTMENT	150
6.4.1	Overview.....	150
6.4.2	Detailed Planning Model	151
6.5	SOLUTION METHOD	156
6.5.1	Fuzzy Adaptive Differential Evolution.....	156
6.5.2	Initialization.....	157
6.5.3	Fuzzy Adaptive Control Parameter Tuning.....	157
6.5.4	Mutation.....	158
6.5.5	Crossover	159
6.5.6	Selection.....	159
6.5.7	Encoding the Proposed Model into FADE.....	159
6.5.8	Parallel Implementation of FADE-based Transmission Network Planning.....	159
6.6	CASE STUDIES.....	161
6.6.1	Experiment Setting.....	161
6.6.2	Simulation Results	162
6.6.3	Sensitivity	166
6.7	CONCLUSION.....	169
7.	A LINEARIZED CO-PLANNING MODEL	171
7.1	INTRODUCTION	171
7.2	GAS MODEL	173
7.2.1	Gas Transportation and Contracts	173
7.2.2	Gas Scheduling	174
7.2.3	Gas System Modeling.....	175
7.3	FORMULATION OF OUR EXPANSION CO-PLANNING MODEL.....	177
7.3.1	Linearized Modeling.....	179
7.3.2	Objective Function and Constraints.....	181
7.3.3	Reliability for the Energy Network.....	183
7.4	CASE STUDIES.....	183
7.4.1	Six-Bus System.....	184
7.4.2	IEEE 118-Bus System.....	188
7.5	CONCLUSION.....	191

8. CONCLUSION AND FUTURE WORK.....193
APPENDIX 197
BIBLIOGRAPHY.....201

LIST OF FIGURES

Fig. 1-1	Structure of power system planning.....	11
Fig. 2-1	A typical set of ratings and membership corresponding to different qualitative judgments.....	28
Fig. 2-2	Dynamic gas flow model.....	53
Fig. 2-3	Gas compressor model.....	55
Fig. 2-4	Gas flow nodal balance model.....	57
Fig. 2-5	An example of using nodal balance to calculate gas flows.....	57
Fig. 2-6	An example of integrated natural gas and power systems.....	60
Fig. 2-7	Interconnection of the Australia's NEM.....	67
Fig. 2-8	Interconnection of the Australia's Gas Market.....	68
Fig. 2-9	An example of gas scheduling in spot markets.....	70
Fig. 3-1	Multi-energy carrier of gas and power systems.....	75
Fig. 3-2	A generalized condition description approach of a component.....	79
Fig. 3-3	Proposed state-space diagram for gas storage.....	80
Fig. 3-4	Experiments with different trails for the capital investment cost.....	86
Fig. 3-5	The Pareto optimality solutions for three cases with objectives of EENS and capital investment cost.....	87
Fig. 3-6	Flow chart of DE solution method.....	88
Fig. 3-7	The summed working volume of gas in gas networks for cases 2 and 3 (note that positive values mean gas to be extracted, negative values mean gas to be stored).....	88
Fig. 3-8	The chosen expansion plans in power networks for three cases.....	89
Fig. 3-9	The chosen expansion plans in gas networks for three cases.....	90
Fig. 3-10	Sensitivity analysis with four parameters for two cases.....	92
Fig. 4-1	Proposed approach for natural gas and power systems expansion co-planning.....	101
Fig. 4-2	Membership function curves.....	106
Fig. 4-3	A three-bus gas and two-bus power systems.....	109
Fig. 4-4	Linepack simulation results for EP and ECP in scenario 3.....	110
Fig. 4-5	Linepack variations for EP and ECP on peak demand day.....	112
Fig. 4-6	Summed total GPG gas demand for EP and ECP in four scenarios on peak demand day.....	113
Fig. 4-7	Comparing the chosen alternatives for separated gas and power system planning versus gas and power system co-planning.....	116
Fig. 5-1	Proposed flexible co-planning method.....	124
Fig. 5-2	Concepts of the life-cycle of capital assets and discounted cash flow.....	125
Fig. 5-3	Flow chart of the proposed HDDE algorithm.....	131
Fig. 5-4	The base case of the combined gas and power systems.....	132
Fig. 5-5	Convergence of 2000 iterations for two cases.....	134
Fig. 5-6	Comparison of the power system for two cases.....	137
Fig. 5-7	Comparison of the flexible co-planning and power system planning.....	138

Fig. 5-8	Results of the gas network planning	139
Fig. 6-1	Parallel model for the FADE-based transmission planning	161
Fig. 6-2	Comparison of FADE to parallel FADE	163
Fig. 6-3	Comparison of convergence of two cases when EA index is 10.....	163
Fig. 6-4	Probability distribution of operating costs with initial setting for case 2	164
Fig. 6-5	CDFs of adjusted risk value to extreme events with various EA indices for case 3	164
Fig. 6-6	The overall cost against various EA indices with different peak loads; and probability of risk to EEs against various EA indices with peak load 6700 MW.....	167
Fig. 6-7	The overall cost against various EA indices with different wind power cost coefficients; and probability of risk to EEs against various EA indices with cost coefficients 14, 42 and -98.....	167
Fig. 6-8	The overall cost against various EA indices with different peak loads; and probability of risk to EEs against various EA indices with total wind power capacity 1200 MW, all WPFs have equal capacities.....	168
Fig. 6-9	The overall cost against various EA indices with different wind power cost coefficients; and probability of risk to EEs against various EA indices with all wind power capacity located at bus 166.....	168
Fig. 7-1	Stair wise linearization for gas supply costs	175
Fig. 7-2	Proposed iterative expansion co-planning framework.....	178
Fig. 7-3	Operation and expansion capital costs in the electricity sector.....	185
Fig. 7-4	Total costs in gas and electricity sectors for cases 3 and 4	186
Fig. 7-5	Operation and expansion capital costs in the gas sector	187
Fig. 7-6	Operation and expansion capital costs in the electricity sector.....	187
Fig. 7-7	Objective and iteration number with various linear sections.....	189
Fig. 7-8	Total costs and energy losses in the planning period for cases 3 and 4	189

LIST OF TABLES

TABLE 2-1	SOME WORKS FOCUSING ON UNCERTAINTIES.....	28
TABLE 2-2	SOME WORKS FOCUSING ON RELIABILITY/SECURITY	36
TABLE 2-3	SOME WORKS FOCUSING ON DEREGULATE ELECTRICITY MARKETS.....	42
TABLE 2-4	SOME WORKS FOCUSING ON INTEGRATING RENEWABLE ENERGY	44
TABLE 2-5	SOME WORKS FOCUSING ON COORDINATED PLANNING.....	46
TABLE 2-6	SOME WORKS FOCUSING ON PLANNING WITH OTHER CONSIDERATIONS	47
TABLE 2-7	FUNDAMENTALS IN GAS NETWORK MODELLING.....	52
TABLE 2-8	TERMS OF REFERENCES OF THE AUSTRALIAN NEM	65
TABLE 2-9	INTERCONNECTOR INPUTS OF THE AUSTRALIA'S NEM.....	66
TABLE 3-1	PARAMETERS OF CANDIDATE PLANS	84
TABLE 3-2	GAS STORAGE STATE RATES	85
TABLE 3-3	EXISTING GAS PIPELINE PARAMETERS.....	85
TABLE 3-4	GAS STUDY PARAMETERS AT NODE.....	85
TABLE 3-5	DISTANCE OF NEWLY FOUND GAS RESERVOIR TO NETWORK NODES.....	86
TABLE 3-6	RESULTS OF THREE CASES.....	91
TABLE 4-1	FUZZY RULES OF FPSO	107
TABLE 4-2	GAS LOAD (TJ/HOUR) AND ELECTRICITY LOAD (MW) OVER ONE DAY FOR THE CASE STUDY	109
TABLE 4-3	COST AND BENEFIT FOR EP AND ECP UNDER THREE SCENARIOS ON ANNUAL BASIS (\$)	110
TABLE 4-4	REGRETS FOR EP AND ECP IN FOUR SCENARIOS	117
TABLE 4-5	RESULTS OF THE BEST ALTERNATIVES FOR EP AND ECP (MONETARY VALUES ARE IN MILLION \$)	117
TABLE 5-1	STUDY PARAMETERS	133
TABLE 5-2	THE EXISTING GAS NETWORK PARAMETERS	133
TABLE 5-3	RESULTS FOR EXPANSION CO-PLANNING	135
TABLE 5-4	ADAPTATION COSTS (MILLION\$) FOR CASE 1 WITH NEW GENERATION CAPACITY UNCERTAINTIES.....	135
TABLE 5-5	COMPARE THE TOTAL COST (MILLION\$) WITH ECP PLAN FOR FLEXIBILITY UNDER UNCERTAINTIES OF NEW GENERATION CAPACITY ENTRY	135
TABLE 6-1	FUZZY RULES OF FADE.....	158
TABLE 6-2	RESULTS COMPARISON FOR CASES 1 AND 2 WITH INITIAL PARAMETERS SETTING	165
TABLE 6-3	PLANS FOR TWO CASES WITH DIFFERENT ECONOMIC ADJUSTMENT INDICES	165
TABLE 6-4	DETAILED RESULTS COMPARED TO SYSTEM WITH 0 MW WIND POWER CAPACITY	169
TABLE 7-1	DETAILED EXPANSION PLANS FOR CASES 3 AND 4.....	190

NOMENCLATURE FOR ABBREVIATIONS

AC	Alternating current
ACP	Annual capital payment
ADLC	Average duration for each load curtailment
AEMO	Australian energy market operator
CDF	Cumulative distribution function
CRF	Capital recovery factor
CS	Compressor station
DC	Direct current
DE	Differential evolution
DG	Distributed generation
DISCOs	Distribution companies
DSM	Demand-side management
EA	Economic adjustment
ECP	Expansion co-planning
EDLC	Expected duration of load curtailment
EEs	Extreme events
EENS	Expected energy not supplied
EFLC	Expected frequency of load curtailment
EIR	Energy index of reliability
EP	Expansion planning
EUE	Expected unserved energy
FACTs	Flexible alternating current transmission system
FADE	Fuzzy adaptive differential evolution
GA	Genetic algorithm
GENCOs	Generation companies
GPG	Gas-fired power generation
HDDE	Historical driven differential evolution
ISO	Independent system operator
KKT	Karush-Kuhn-Tucker
LNG	Liquefied natural gas
LOEE	Loss of energy expectation
LOLC	Loss of load cost
LOLE	Loss of load expectation
LOLP	Loss of load probability
LP	Line-pack
MC	Monte Carlo
MNSP	Market network service provider
MTTF	Mean time to failure
MTTR	Mean time to repair
NERC	North American Electric Reliability Corporation

NEM	National electricity market
NPV	Net present value
NSW	New South Wales
OPF	Optimal power flow
PDF	Probability density function
PLC	Probability of load curtailment
POE	Probability of exceedance
PSO	Particle swarm optimization
QLD	Queensland
RRN	Regional reference node
SA	South Australia
SAIDI	System average interruption duration index
SAIFI	System average interruption frequency index
SIS	Sequential importance sampling
STTM	Short-term trading market
TAS	Tasmania
TEP	Transmission expansion planning
ToP	Take-or-pay
TRANSCOs	Transmission companies
UC	Unit commitment
UGS	Underground gas storage
WPFs	Wind power farms
VCR	Value of customer reliability
VIC	Victoria

LIST OF PUBLICATIONS INCLUDED AS PART OF THIS THESIS

The following publications as the major Ph.D. research results of this candidate are included as part of this thesis.

- [P1] K. Meng, Z.Y. Dong, Y. Zheng, **J. Qiu** and K. P. Wong, “Optimal allocation of ESS in distribution systems considering wind power uncertainties”, *Proc. 2012 the International Conference on Power System Control, Operations and Management (APSCOM)*, Hong Kong, Jul. 2012.
- [P2] F. J. Luo, Z. Y. Dong, Y. Y. Chen, E. Pozorski, **J. Qiu**, Y. Zheng, Y. Xu and K. Meng, “Constructing the power cloud data centre to deliver multi-layer services for smart grid”, *Proc. 2012 APSCOM*, Hong Kong, Jul. 2012.
- [P3] **J. Qiu**, Z. Y. Dong, K. Meng, Y. Zheng, Y. Y. Chen and H. Q. Tian “Risk sharing strategy for minimizing imbalance costs of wind power forecast errors”, *Proc. 2013 IEEE Power and Energy Society (PES) General Meeting*, Vancouver, Canada, Jul. 2013.
- [P4] **J. Qiu**, Z. Y. Dong, G. Chen, H. Q. Tian, Y. Y. Chen, and F. J. Luo, “Expansion co-planning with uncertainties in a coupled energy market”, *Australian Universities Power Engineering Conference (AUPEC2013)*, Tasmania, accepted to be published.
- [P5] H. Q. Tian, Z. Y. Dong, **J. Qiu**, G. Chen, Y. Y. Chen, and W. F. Yao, “A new reliability criterion for energy market expansion planning”, *AUPEC 2013*, Tasmania accepted to be published.
- [P6] **J. Qiu**, Z. Y. Dong, H. Q. Tian and Y. Zheng, “Apply theories of motivation to project-based power planning entities”, *International Conference on Management Innovation and Business Innovation (ICMIBI) 2013*, Singapore, accepted to be published.

- [P7] Y. Zheng, Z. Y. Dong, F. J. Luo, K. Meng, **J. Qiu** and K. P. Wong “Optimal allocation of energy storage system for risk mitigation of DISCOs with high renewable penetrations,” *IEEE Trans. Power Systems*, vol. 29, no. 1, pp. 212-220, Jan. 2014.
- [P8] Y. Zheng, Z. Y. Dong, Y. Xu, K. Meng, J. H. Zhao and **J. Qiu** “Electric vehicle battery charging/swap stations in distribution systems: comparison study and optimal planning,” *IEEE Trans. Power Systems*, vol. 29, no. 1, pp. 221-229, Jan. 2014.
- [P9] **J. Qiu**, Z. Y. Dong, J. H. Zhao, K. Meng, H. Q. Tian and K. P. Wong “Expansion co-planning with uncertainties in a coupled energy market”, accepted by *2014 IEEE PES General Meeting*, Washington D. C., USA, Jul. 2014.
- [P10] **J. Qiu**, Z. Y. Dong, J. H. Zhao, K. Meng, Y. Zheng and D. Hill, “Expansion planning of integrated gas and power markets in a coupled energy market,” accepted for *submitting full paper to the special issue on low carbon economy on IEEE Trans. Power Systems*, 2014.
- [P11] F. J. Luo, J. H. Zhao, **J. Qiu**, J. Foster, Y. Y. Peng and Z. Y. Dong, “Assessing the transmission expansion cost with distributed generation: an Australian case study,” accepted by *IEEE Trans. Smart Grid*, 2014.

In addition, the candidate has submitted ten manuscripts for publication, which are currently under review. These submitted manuscripts are listed below.

- [SP1] Fengji Luo, Z.Y. Dong, Y.Y. Chen, K. Meng, **J. Qiu**, J.H. Zhao, Eric Pozorski, and K.P. Wong, “Cloud computing infrastructure for next-generation power system: conception, prospective, and applications, ” *IEEE Trans. Industrial Informatics*, current under 2nd review.
- [SP2] Y. Y. Chen, Z. Y. Dong, F. J. Luo, K. Meng, **J. Qiu** and K. P. Wong, “A multi-constrained optimal power flow method with discrete control variables”, *IEEE Trans. Power Systems*, submitted.

- [SP3] Y. Y. Chen, Z. Y. Dong, F. J. Luo, K. Meng, **J. Qiu** and K. P. Wong, “A collector system layout optimization model for large-scale offshore wind farms”, *IEEE Trans. Sustainable Energy*, submitted.
- [SP4] **J. Qiu**, Z. Y. Dong, J. H. Zhao, Y. Xu and Y. Zheng, “Multi-stage flexible expansion co-planning with uncertainties in a combined electricity and gas market,” *IEEE Trans. Power Systems*, submitted.
- [SP5] **J. Qiu**, Z. Y. Dong, K. Meng, F. J. Luo and K. P. Wong “Coordination of transmission and generation capacity planning in a coupled energy market,” *IEEE Trans. Power Systems*, submitted.
- [SP6] **J. Qiu**, Z. Y. Dong, J. H. Zhao, K. Meng, Y. Zheng and K. P. Wong “Expansion co-planning considering gas impacts on electricity markets,” *IEEE Trans. Power Systems*, submitted.
- [SP7] **J. Qiu**, Z. Y. Dong, J. H. Zhao, K. Meng, Y. Zheng and H. Q. Tian “Insurance strategy for minimizing imbalance costs of wind power in real-time markets,” *IEEE Trans. Sustainable Energy*, current under 2nd review.
- [SP8] **J. Qiu**, Z. Y. Dong, J. H. Zhao, K. Meng, F. J. Luo and K. P. Wong “An economic adjustment approach for probabilistic transmission expansion planning,” *IEEE Trans. Power Systems*, submitted.
- [SP9] **J. Qiu**, Z. Y. Dong, J. H. Zhao, K. Meng, Y. Zheng and K. P. Wong “Expansion co-planning for shale-gas integration in a combined energy market,” *IEEE Trans. Power Systems*, submitted.
- [SP10] **J. Qiu**, Z. Y. Dong, J. H. Zhao, K. Meng, Y. Zheng and K. P. Wong “A linear programming approach for expansion co-planning in energy markets,” *IEEE Trans. Power Systems*, submitted.

I warrant that I have obtained, where necessary, permission from the copyright owners to use any third party copyright material reproduced in the thesis, or to use any of my own published work (e.g. journal chapters) in which the copyright is held by another party (e.g.

publisher, co-authors).

ABSTRACT

Power system planning plays an essential role in maintaining the economic, secure and reliable operations of power systems. Following the deregulation of electricity industry, power system planning encounters many challenges as a result of the advent of various market participants, such as market uncertainties and conflicting objectives. Moreover, due to the growing concerns on climate change around the world, natural gas becomes more economically competitive among traditional fossil fuels, leading to the proliferation of gas-fired power generation (GPG) in the power sector. In a market environment, the access to affordable and reliable gas sources can significantly influence the competitiveness of market participants, and then the power system operations consequently. Therefore, power system planning should integrally take into account the gas infrastructure.

Fuel availability and prices are treated as uncertain inputs in conventional power system planning methods, which usually suffer from inaccurate market signals (e.g. congestion costs) and insufficient knowledge of network weakness. This thesis research focuses on the proposal of an expansion co-planning framework for gas and electricity transmission infrastructure in a combined energy market. The expansion co-planning approach is able to reflect the dynamic, nonlinear and non-convex nature of the integrated gas and electricity systems. In addition to the reliability/security planning criterion, this research aims to enhance the market efficiency of assets through the planning practice, e.g. facilitating competition, alleviating congestion, improving social welfare, minimizing risks, etc.

The proposed expansion co-planning framework can be used to guide the energy industry to form a holistic approach to the strategic planning of future grids including gas and electricity networks, subject to various interacting constraints. It has covered a variety of aspects in planning, including a generalized reliability evaluation method for coupled gas and electricity networks, market timeline mismatch, multi-objectives, tackling interactive constraints, stochastic programming, risk management, energy networks' vulnerability to extreme events

caused by climate change, and linearization techniques. With regard to planning solution techniques, a range of up-to-date methods have been applied or developed, including differential evolution, decision making analysis with the fuzzy particle swarm optimization, historical driven differential evolution with variance reduction techniques, fuzzy adaptive differential evolution with parallel implementation, linear programming, mixed-integer programming, iterative algorithm, etc.

A number of benchmark test systems have been used to demonstrate the effectiveness of the proposed expansion co-planning approach. Comparative studies to existing approaches in the literature, where applicable, have also been conducted. The real applicability of the proposed approach has been verified by simulation results.