OPTIMAL DESIGN AND SCHEDULING OF AN INTEGRATED CENTRALIZED AND DECENTRALIZED ENERGY GENERATION SYSTEM

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ABSTRACT

Most electricity worldwide is supplied from the established centralized energy generation (CEG) system network which mainly operates using fossil fuels. An alternative decentralized energy generation (DEG) system has emerged with the advantage of generating electricity from locally available resources (usually renewable energy) for local consumption. DEG systems could avoid significant power losses during transmission in the CEG network and reduce the reliance on fossil fuels. These DEGs however, are geographically scattered and their resources are intermittent. One notable problem is that, at one point of time, some DEGs may have excess electricity and some may have electricity deficits; depending on the resource availability and the electricity consumption pattern. Weather-depending resources such as solar and wind energy could also affect the system's reliability. The energy gaps between one DEG to another can be solved, provided that the DEGs are integrated at the distribution level whereas the reliability issue can be overcome by integrating multiple DEGs to the existing CEG (which has a more stable electricity supply) at the transmission level. To deploy this complex integrated energy system, key decision parameters such as selection of technologies and their capacities, interactions between different units, overall system efficiency and costing at their optimum level have to be determined. There are limited studies in the literature regarding the wide-scale integration of DEGs with CEG and a lack of comprehensive optimization approach to solve for the system's design and scheduling. To fill these gaps, this research aimed to develop a novel targeting and optimization methodology for the design and scheduling of the DEG-CEG integrated energy system. A new numerical DEG-CEG integration framework was developed based on two enhanced Power Pinch approaches: (i) Extended Power Pinch Analysis for on-grid DEG system, and (ii) Extended Electrical Power System Cascade Analysis for CEG system with generation flexibility. The numerical framework optimized only the system's energy efficiency. A mixed integer nonlinear programming (MINLP) model was then developed to study the DEG-CEG system more holistically in terms of energy efficiency and costing, as well as to validate the optimal solutions resulted from the numerical framework. Both approaches were demonstrated using a hypothetical case study – an integrated energy system with multiple DEGs (operating using solar, wind and biomass energy) at different locations connected to one CEG (operating using natural gas) to fulfil power demand from residential, commercial and industrial sectors. From energy-efficient aspect, the numerical framework resulted in the system operating at an efficiency of 77 %, while the MINLP model showed 80.7 %. The difference of 3.7 % confirms the relevance of the numerical DEG-CEG integration framework as a systematic and effective energy planning tool in solving the design and scheduling problems of a power system. In term of costing, the MINLP model revealed that the system can achieve 77 % with a total cost of RM 936 million/y. Nevertheless, the numerical method is still an important analytical tool as the analysis provides visual insights that can be easily understood and appreciated by users like energy engineers and policymakers.

ABSTRAK

Kebanyakan elektrik di dunia dibekalkan daripada rangkaian sistem penjanaan tenaga berpusat (CEG) yang beroperasi terutamanya menggunakan bahan api fosil. Satu sistem tenaga alternatif iaitu sistem penjanaan tenaga desentralisasi (DEG) telah muncul dengan kelebihan untuk menjana tenaga elektrik dari sumber tempatan yang tersedia (biasanya tenaga boleh diperbaharui) untuk penggunaan tempatan. Sistem DEG boleh mengelakkan kerugian kuasa yang besar semasa penghantaran dalam rangkaian CEG dan mengurangkan pergantungan kepada bahan api fosil. Walau bagaimanapun, lokasi DEG ini bertaburan dan sumber mereka terputus-putus. Satu masalahnya ialah, pada satu ketika, sesetengah DEG mungkin mempunyai lebihan elektrik dan sesetengahnya mengalami kekurangan bekalan elektrik; bergantung kepada ketersediaan sumber dan profil penggunaan elektrik. Sumber cuaca seperti tenaga suria dan angin juga boleh menjejaskan kebolehpercayaan sistem. Jurang tenaga sesama DEG boleh diselesaikan apabila sistem-sistem DEG diintegrasikan pada tahap pengagihan manakala isu kebolehpercayaan dapat diatasi dengan mengintegrasikan pelbagai DEG kepada CEG yang sedia ada (yang mempunyai bekalan elektrik yang lebih stabil) pada tahap penghantaran. Bagi melaksanakan sistem tenaga bersepadu kompleks ini, parameter keputusan utama seperti pemilihan teknologi dan kapasitinya, interaksi antara unit yang berbeza, kecekapan dan kos optimum keseluruhan sistem perlu ditentukan. Daripada kajian literatur, kajian mengenai penggabungan DEG dengan CEG berskala besar dan pendekatan pengoptimuman yang komprehensif untuk menyelesaikan reka bentuk dan penjadualan sistem adalah terhad. Untuk mengisi jurang penyelidikan ini, kajian ini bertujuan untuk menghasilkan metodologi penyasaran dan pengoptimuman yang novel untuk mengoptimumkan reka bentuk dan penjadualan sistem tenaga bersepadu DEG-CEG. Satu kerangka kerja integrasi DEG-CEG berangka baharu dihasilkan daripada gabungan dua pendekatan Power Pinch yang telah dipertingkatkan: (i) Extended Power Pinch Analysis untuk sistem DEG di-grid, dan (ii) Extended Electrical Power System Cascade Analysis untuk sistem CEG dengan penjanaan fleksibel. Rangka berangka hanya mengoptimumkan kecekapan tenaga sistem. Model MINLP kemudiannya dihasilkan untuk mengkaji sistem DEG-CEG dengan lebih holistik dari segi kecekapan tenaga dan kos, serta untuk mengesahkan penyelesaian optimum hasilan kerangka berangka. Kedua-dua pendekatan ini didemonstrasikan melalui kajian kes hipotetikal - sistem tenaga bersepadu dengan pelbagai DEGs (beroperasi menggunakan tenaga solar, angin dan biomas) di lokasi yang berbeza yang berkaitan dengan satu CEG (beroperasi menggunakan gas asli) untuk memenuhi permintaan elektrik daripada sektor kediaman, komersial dan perindustrian. Dari aspek kecekapan tenaga, kerangka berangka membuktikan bahawa sistem tersebut dapat beroperasi pada kecekapan 77 %, sementara model MINLP menunjukkan 80.7 %. Perbezaan 3.7 % ini mengesahkan kesesuaian kerangka integrasi DEG-CEG berangka sebagai alat perancangan tenaga yang sistematik dan berkesan dalam menyelesaikan masalah reka bentuk dan penjadualan sistem kuasa. Dari segi kos pula, keputusan model MINLP menunjukkan bahawa sistem tersebut boleh mencapai 77 % dengan jumlah kos RM 936 juta setahun. Walau bagaimanapun, kaedah berangka masih merupakan alat analisis penting kerana ia memberikan pandangan visual yang mudah difahami dan dihargai oleh pengguna seperti jurutera tenaga dan penggubal dasar.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	-	Alternating current
AD	-	Anaerobic digestion
AEEND	-	Amount of Excess Electricity for the Next Day
BaU	-	Business as usual
BBFB	-	Biomass bubbling fluidized bed
CAES	-	Compressed air energy storage
CEG	-	Centralized energy generation
CPCC	-	Continuous Power Composite Curve
CSP	-	Concentrated solar power
DC	-	Direct current
DCC	-	Demand Composite Curve
DEG	-	Decentralized/distributed energy generation
DoD	-	Depth of discharge
EPoPA	-	Extended-Power Pinch Analysis
ES	-	Energy storage
ESCA	-	Electrical Power System Cascade Analysis (amended from previous name "Electric System Cascade Analysis")
FiT	-	Feed-in tariff
GAMS	-	General Algebraic Modelling System
GCC	-	Grand Composite Curve
GDX	-	GAMS Data Exchange
HOMER	-	Hybrid Optimization of Multiple Energy Resources
HPS	-	Hybrid power system
IBS	-	Integrated biomass and solar
IPP	-	Independent power producers
LCOE	-	Levelized cost of electricity
Li-ion	-	Lithium-ion
LLP	-	Loss of load probability
LP	-	Linear programming
MEPoPA	-	Modified Extended-Power Pinch Analysis

MILP - Mixed integer linear programming
MINLP - Mixed integer nonlinear programming
MOES - Minimum Outsource Electricity Supply
MO-RHO - Multi-objective receding horizon optimization
NaS - Sodium-sulphur
NGCC - Natural gas combined cycle
Ni-Cd - Nickel-cadmium
NO_X - Nitrogen oxides
O&M - Operating and maintenance
OECD - Organization for Economic Cooperation and Development
OSEC - Outsourced and Storage Electricity Curves
PA - Pinch Analysis
PCC - Power Composite Curve
PCT - Power Cascade Table
PI - Process Integration
PoPA - Power Pinch Analysis
P-PoPA - Probability-Power Pinch Analysis
PV - Photovoltaic
RE - Renewable energy
SAHPPA - Stand-Alone Hybrid System Power Pinch Analysis
SCC - Source Composite Curve
SCT - Storage Cascade Table
SHARPS - Systematic Hierarchical Approach for Resilient Process Screening
SO_X - Sulphur oxides

LIST OF SYMBOLS

$AEEND$ - Amount of Excess Electricity for the Next Day

BES - Cumulative energy in battery (apply to modified SCT only to differentiate ES at DEG)

BES_{new} - New cumulative energy in battery (apply to modified SCT only to differentiate ES at DEG)

C - Power to be charged

Cap - Generator capacity (Cap_1 – first cascading, Cap_2 – second cascading)

Cap_{new} - New generator capacity (for iteration purpose)

$Cap_{1,op}$ - “First optimal” generator capacity

$Cap_{2,op}$ - “Second optimal” generator capacity

D - Power to be discharged

DL - Average power distribution loss at the grid network

E - Energy level in storage/Cumulative energy in ES

EC - Energy consumption

E_{exc} - Excess energy in power system

E_{in} - Energy input generated on-site at DEG or CEG on daily basis

E_{new} - New cumulative energy in ES

E_{out} - Energy output delivered to the local demand at DEG on daily basis

E_{req} - Required energy in power system

Eff_{ES} - Energy storage charging/discharging efficiency

Eff_{iv} - Converter efficiency

EG - Total grid energy

ERC - Energy-related capacity of the energy storage

ERC_{actual} - Actual energy-related capacity of the energy storage after DoD consideration

G - Power generation

G_{lo} - Lower generation limit

G_{up} - Upper generation limit

GPR - Grid power rating

HR - Heat rate of power generator

HR_o - Heat rate of power generator at full-load

L - Power demand/Power load

L_{max} - Maximum power demand

LF - Load factor/Operating load

$MOES$ - Minimum Outsource Electricity Supply

N - Net energy

O_d - Amount of power outsourced by the deficit DEG

O_s - Amount of power delivered from the surplus DEG before entering the distribution network

OP_{eff} - Overall plant efficiency (apply in Chapter 5 for Extended ESCA on a single DEG plant)

P - Power of charging/discharging (general)

P_{demand} - Actual amount of net power demand from DEGs to be delivered by CEG after transferring through the transmission and distribution network

P_{net} - Net power resulted from the power-sharing among all DEGs

P_{supply} - Actual amount of net power surplus from DEGs to be addressed to CEG after transferring through the transmission and distribution network

PD - Percentage difference

PP - Power Pinch Point

PRC - Power-related capacity of the energy storage

R - Potential range for $Cap_{2,op}$

r - Percentage of heat rate increase

T - Period of analysis

t - Time interval

TDR - Plant's turndown ratio

TEC - Total energy consumption

TL - Average power transmission loss at the grid network

η - Overall system energy efficiency (apply in Chapter 6 for DEG-CEG integration framework)

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Energy drives a nation’s development. From basic living requirement to the operations in industrial and commercial activities, energy plays a vital role. From Figure 1.1, it is projected that the world will reach an incline of energy consumption about 28 %, from 575 quadrillion British thermal units (Btu) in 2015 to 736 quadrillion Btu by 2040 (U.S. EIA, 2017). The increment of energy demand is mostly attributed to non-Organization for Economic Cooperation and Development (OECD) countries, including China and India. The key drivers to the rising energy demand in these regions are strong economic growth, rapid population increase and energy market liberalization (U.S. EIA, 2017).

To cope with energy security and sustainability issues against the growing energy consumption, the world has gradually inclined into the selection of cleaner resources and more efficient technologies since the last few decades. A study conducted by U.S. EIA (2017) claimed that the world’s carbon dioxide emission resulted from power generation activities has been slowed to an average of 0.6 % per year compared to 1.3 % per year (from 1990 to 2014) since 2015. This is mainly owing to the increase in energy efficiency initiatives as well as a gradual switch of resources from coal to natural gas and renewable energy (RE).

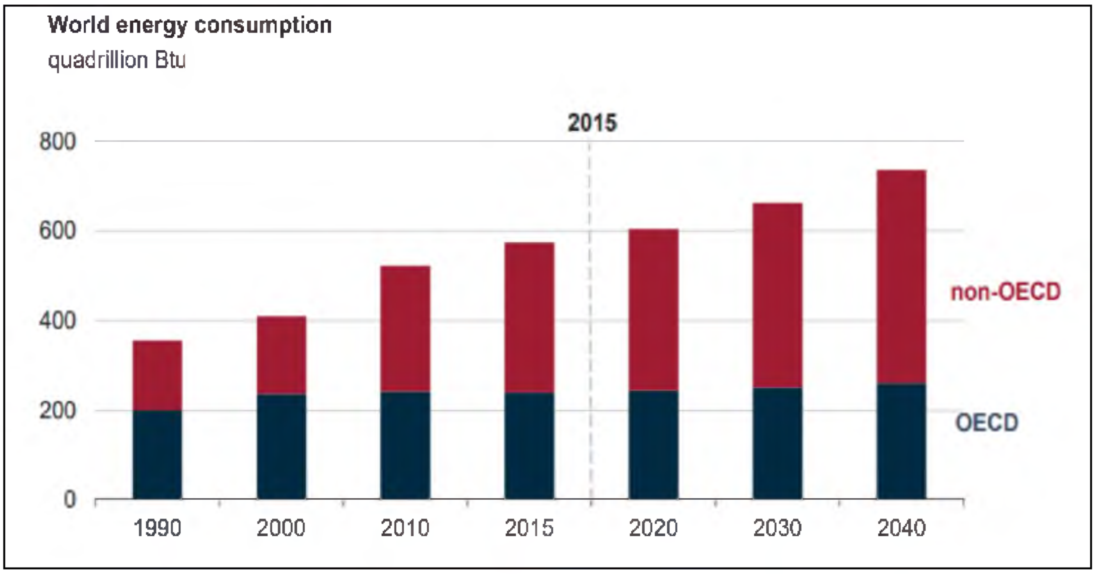

Figure 1.1 Records and projections of world energy consumption from 1990 to 2040 (U.S. EIA, 2017)

As shown in Figure 1.2, the global consumption of traditional fuels such as diesel and gasoline is facing a declining fashion, while the use of RE fuels (such as ethanol and biodiesel) has been a gradual increase. In the year 2012, RE has accounted for 23 % of the global electricity generation, which is equivalent to 4,892 TWh (16,692.2 Btu). This indicates that RE has begun to gain popularity and has potential in replacing the non-RE in the future.

Based on Figure 1.3, hydropower remains as the largest contributor of renewable electricity. Wind and solar energy have recently become the fastest-growing renewable technologies compared to others, owing to the dramatic fall of their installation price (U.S. EIA, 2016). Wind and solar energy have become the dominant investment fields viewing from the global total RE investment in 2012 (Figure 1.4), with an approximate of 50 billion USD and 20 billion USD allocated. Dealing with the growing penetration of RE into the current energy system, even more challenging with the intermittent supplies from solar and wind power, the planning of a more flexible and reliable power generation system to adapt the unpredicted changes is deemed the next important agenda.

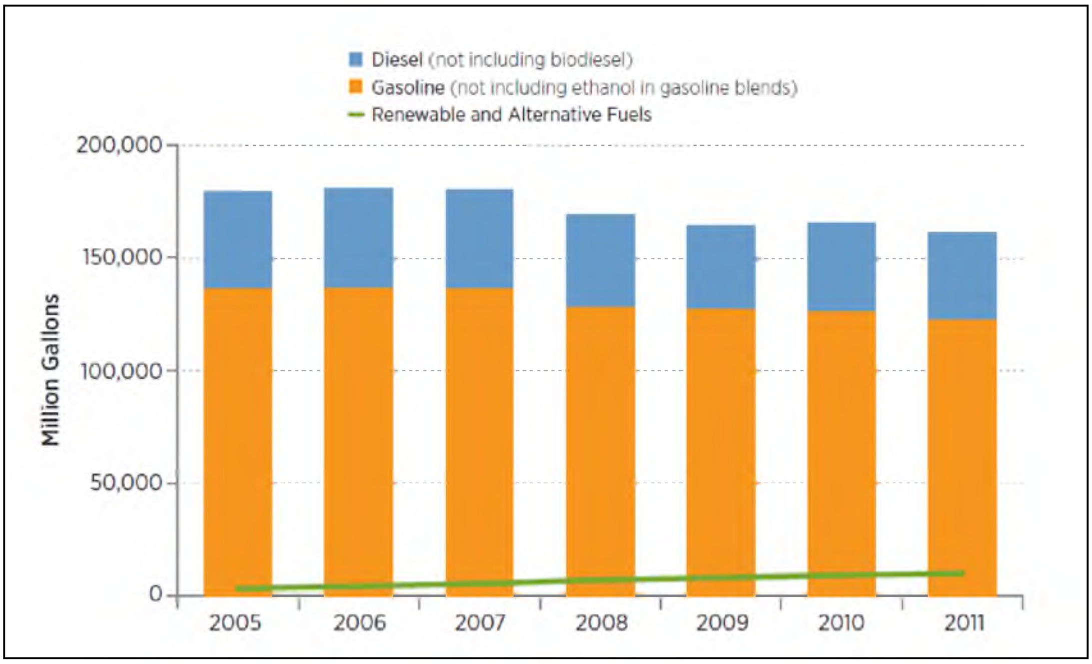

Figure 1.2 Global consumption of fuel (NREL, 2013)

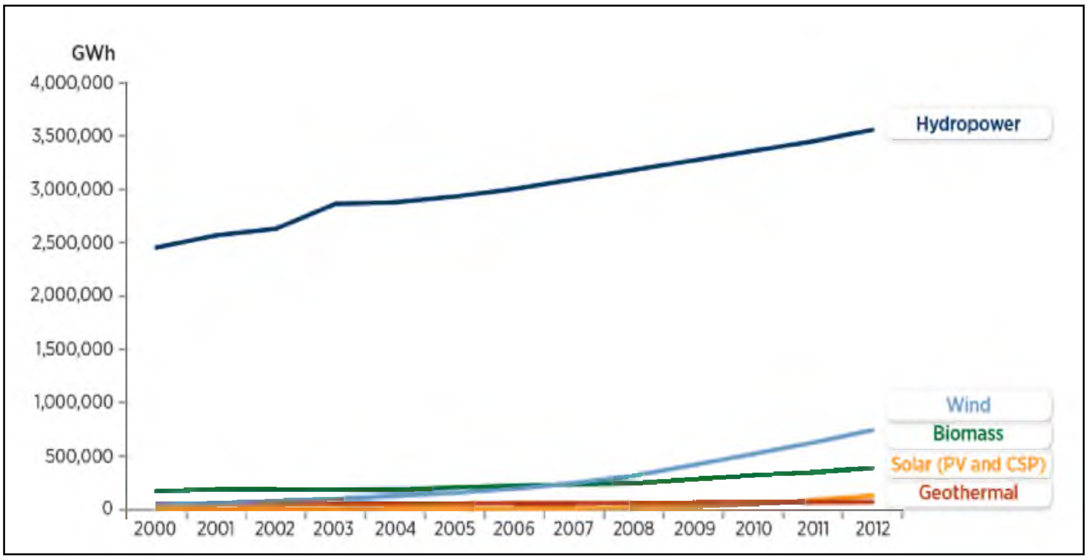

Figure 1.3 Worldwide renewable energy generation by technology (NREL, 2013)

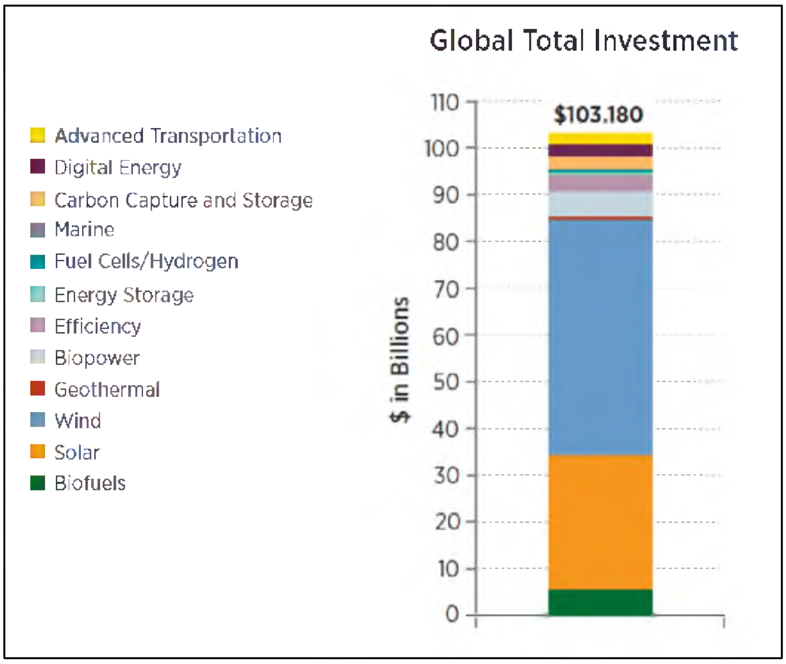

Figure 1.4 Global total investment in different renewable energy-related sectors in year 2012 (NREL, 2013)

1.1.1 Centralized Energy Generation

At present, a vast majority of electricity generated worldwide is from the conventional centralized energy generation (CEG) system – a large-scale electricity generation facility (about 2,000 to 9,000 MW), connected to a network of high-voltage transmission lines (U.S. EPA, 2018a) to provide electricity to an entire region. CEG operates based on coal, gas and nuclear power plants. Some generates from hydropower plants, wind and solar farms. Normally CEG serves high-demand urban areas; however, the facilities are usually located away from the end-users (Origin Energy, 2015). Economies of scale in generation facilities and technical viability are the major factors of successful implementation of CEG (Martín-Martínez *et al.*, 2017).

In the advent of energy demand rise, CEG which mostly utilizes fossil fuels for combustion process cannot be a prolonged technology, considering the carbon emission, supply security due to depletion of non-RE resources and costing issues. Despite the enormous and bulky infrastructures, CEG is vulnerable in term of stability and reliability under unforeseen events (Momoh *et al.*, 2012). There is also a significant amount of energy wasted during the power transmission and distribution. On average, only 28 to 32 % of the generated electricity is delivered to the end-consumers (Jiang *et al.*, 2009; The World Bank Group, 2018). These losses are cumulatively accounted as “line loss” (U.S. EPA, 2018a).

1.1.2 Decentralized Energy Generation

Nowadays the power generation trend has become more localized with the employment of decentralized energy generation (DEG) system. The interest in the development of DEG has been catalysed by environmental policies and regulations as well as governmental subsidies, such as net metering, advancement of DEG technologies, feed-in tariff (FiT) scheme etc. (Momoh *et al.*, 2012).

A DEG unit has a small-scale energy generation, where its capacity normally ranges between 1 kW to 250 MW (Ogunjuyigbe *et al.,* 2016). Opposite to the CEG, DEG is not directly connected to the bulk transmission system and is not centrally dispatched. It is constructed within the distribution of a power network that is closer to consumers (Allan *et al.*, 2015) and produces electricity at the local level. DEG enables electricity access to remote housing areas with geographical constraint where the grid network connection is difficult to reach (Fadaee and Radzi, 2012).

Using renewable resources, DEG gives indisputable environmental advantages, due to its reduced global warming impact, inexhaustibility and lower environmental costs (Vezzoli *et al.*, 2015). In term of operation, when power is distributed locally, the “line loss” can be reduced. However, intermittency of the renewable resources may greatly affect the power quality and reliability of DEG system. In economic aspect, DEG, which is usually employed in smaller economic scale, is difficult to gain a profit margin. Stiff competition of its fuel cost with non-RE and the lack of technologies maturity are factors that makes DEG less cost-attractive compared to CEG.

1.2 Problem Statement

Although the utilization of RE for power generation becomes prevalent, their sources are, however, geographically scattered and intermittent. Harnessing these RE sources are therefore more suitable at DEG level compared to CEG. As more RE-based DEG units emerge at different locations where the sources can be easily accessed, one notable problem arising is that some DEGs may have excess electricity and some may have insufficient electricity to self-sustain. The scenario is very much dependent on local resource availability and the local consumption pattern. These energy gaps between one DEG to another can be solved, provided that they are integrated to form a grid network at the distribution level. Even if the DEGs are integrated, weather-depending renewable resources such as solar and wind will pose an additional problem to the DEG system in term of reliability. This can be overcome by integrating multiple DEGs to the existing CEG, which has a more stable electricity supply, at the transmission level. Moreover, most places in the world already have an established CEG network. The benefits of integrating DEGs with CEG are to maximize the utilization of local renewable energy while relying less on the CEG. Reduced reliance of CEG can avoid large amount of power losses during transmission and the consumption of fossil fuels (as CEG systems mainly operates using fossil fuels).

The implementation of such a complex DEG-CEG integrated system requires careful and thorough planning. In term of scheduling, the availability of resources and deficiency of demands for different DEG units are not the same. The operation of existing CEG is no longer the same and needs to be more flexible when DEGs are integrated into the CEG to form a new power system network. Key decision parameters such as selection of technologies and their capacities, interconnections between different units, overall system efficiency and costing at their optimum level are to be determined. However, there is a lack of studies in the literature regarding the wide-scale integration of DEG with CEG as well as a comprehensive optimization approach to solve for the design and scheduling of the system. In order to fill the gaps, this research will study the large-scale integration of DEG-CEG system, along with a systematic and effective approach for targeting and optimizing the integrated energy system.

1.3 Research Objectives

Based on the problem statement, this research aims to develop a novel targeting and optimization methodology for the design and scheduling of an integrated energy system (constitutes of multiple DEGs connected to one CEG) which is technically and economically sound.

The targeting and optimization methodology developed includes:

(a) A new numerical integration framework to design and schedule the integrated CEG-DEG system
(c) A holistic mathematical model to design and schedule the integrated CEG-DEG system considering cost and energy efficiency factors

The developed methodology is then demonstrated on an illustrated case scenario which represents the integrated energy system, constitutes of multiple DEGs operating with a varied combination of energy resources and demand at different locations and are connected to one CEG. The following parameters could be determined:

(a) The optimal capacities of DEG and CEG systems
(b) The optimal power generation and charging/discharging schedule of DEG and CEG systems
(c) The interaction and power-sharing between DEG and CEG systems in the grid network
(d) The overall performance of the integrated energy system in term of energy efficiency and total system cost

1.4 Research Scope

To achieve the intended research objectives, the scope of research has been drawn as followed:

(a) Studying the state-of-the-art development and technologies related to centralized (CEG) and decentralized energy generation (DEG) systems and identifying gaps and potential improvement of Power Pinch and mathematical modelling approaches for power system optimization.

(b) Improving the existing algorithms in Power Pinch approaches to solve for more realistic power plant scenarios. The improvement is specifically targeted on the supply-side management of the power plant itself and the entire energy system. Specific scopes include:
   (i) Extending the established Power Pinch Analysis (PoPA) by incorporating the role of grid network into a Hybrid Power System (HPS) through strategies of purchasing or selling of grid electricity
   (ii) Extending the established Electrical Power System Cascade Analysis (ESCA, term amended from previous “Electric System Cascade Analysis”) in consideration of flexibility in thermal power generation defined by the change of heat rate with the plant’s load factor.

(c) Integrating the newly extended Power Pinch methods in (b) into a systematic numerical framework to determine the optimum design and scheduling of the integrated energy system and the interactions between the DEG and CEG units. Power distribution and transmission losses occurring at the grid network are addressed.

(d) Developing a holistic and comprehensive superstructure-based mathematical model that replicates the integrated energy system in (c) and solves for the system’s optimum design and scheduling using General Algebraic Modelling Systems (GAMS) software. Specific scopes include:

    (i) Developing a mixed integer nonlinear programming (MINLP) model that is time-oriented (hourly basis) and includes factors like heat rate variations from the plant's operating load, efficiency losses due to storage's charging or discharging, current conversion, transmission and distribution losses to the power transfer and cost into the analysis
    (ii) Evaluating the reliability and practicality of the integrated energy system model in both technical (i.e. energy efficiency of the entire system) and economic (i.e. overall system cost) aspects

(e) Examining the applicability of the developed numerical framework in (c) in term of accuracy and optimality by verifying and comparing the results obtained using the mathematical model developed in (d). Both approaches are used to solve for one identical case scenario.

1.5 Research Contributions

Through the work conducted in this PhD research, several key contributions can be identified from this research. They are listed as follows:

(a) Improvement in the field of power system optimization
The optimization approaches developed in this research address the new form of losses due to transmission and distribution power transfer, as well as the increment of heat rate due to the different operating loads in a power plant. The inclusion of these elements into the analysis leads to a more holistic, realistic and better-optimized power system design and scheduling. Unnecessary expenses or unexpected system failure due to under-sizing or oversizing issues can thus be avoided.

(b) Facilitation in decision and policy-making
The numerical method developed in this work is able to provide users like energy engineers and policy-makers valuable insights to the problem being solved. Users can have a full control and understanding on how to match the

power supply and demand in a manual but systematic way. Measures of improvement can be easily identified hence it facilitates the decision-making process. The analysis results are also useful references for energy system planning and policy-making.

(c) Commercialization value of research product

The formulated energy model can be matured and packaged into a commercial software, specialized in solving various power-related scenarios. The inclusiveness of the model allows a large volume of data to be processed in a short time, increases the variation of the system configuration with a combination of intermittent and non-intermittent sources together with different renewable and non-renewable based technologies.

Several publications have been produced from this research as a part of intellectual contributions. They are enumerated in the List of Publications.

1.6 Organization of Thesis

This thesis contains eight chapters. Chapter 1 is the research introduction, highlighting the background of the study, problem statement, research objectives, scope and contributions. Chapter 2 is the literature review where state-of-art of power systems and the technologies are presented. In the same chapter, previous studies on power system optimization approaches, mainly on the Power Pinch and mathematical modelling, are also reviewed and analyzed to search for the research gaps. Chapter 3 describes the general research methodology in order to achieve the targeted objectives. For the research findings, they are reported in separate chapters (Chapter 4, 5, 6 and 7). Last but not least, Chapter 8 concludes all the research output from this study and recommends possible future work to be explored.

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