



Faculty of Electrical Engineering

**IMPACTS ON POWER FLOW AND QUALITY OF PENETRATING
50MW WIND PLANT INTO STAND ALONE GRID**

Suhaib Salam Mohammed Ahmed AL-Kaiali

Master of Electrical Engineering (Industrial Power)

2017

**IMPACTS ON POWER FLOW AND QUALITY OF PENETRATING 50MW
WIND PLANT INTO STAND ALONE GRID**

SUHAIB SALAM MOHAMMED AHMED AL-KAIALI

**A thesis submitted
in fulfilment of the requirements for the degree of Master of Electrical
Engineering (Industrial Power)**

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2017

DECLARATION

I declare that this dissertation entitled “Impacts on Power Flow and Quality of Penetrating 50MW Wind Plant into Stand Alone Grid” is the result of my own research except as cited in the references. The dissertation has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : 

Name : SUHAIB SALAM AL-KAIALI

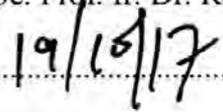
Date : 12/10/2017

APPROVAL

I hereby declare that I have read this project and in my opinion this dissertation is sufficient in terms of scope and quality for the award of Master of Electrical Engineering (Industrial Power).

Signature : 

Supervisor Name : Assoc. Prof. Ir. Dr. Rosli Bin Omar

Date : 

DEDICATION

To my beloved mother, handsome father and best and only one brother Harith My aunty Zainab and Uncle Jasim and Laith need to dedicate also my special friend and brothers in Iraq, Malaysia & Oman.

To Salim AL-Rubkhi Ahmed Abdul-Jalil , Ahmed Zuhair, Mustafa Ayad, Thamer Emad , Laith Nazzeh Bini Melham , My sister Zainab Majeed and Salma Mansour. All of them dedicate who encourage me to complete my study and make the possibility to overcome the ascription and help me to complete my study.

ABSTRACT

The demand for electricity is continuously growing due to the development in community's macro-economic parameters; Population and the Gross Domestic Product (GDP). Currently, electricity is mainly generated from conventional sources including fossil fuels (oil, coal, gas, etc.) and nuclear fuel. The increase in demand increases the concerns about depletion of fossil fuels, increasing of carbon dioxide (CO₂) and other emissions, environmental pollution, and climate changes. Global energy agencies have been urged to look for sustainable and environment friend resources. Renewable energy resources especially wind and solar resources are found ambitious sources that can be developed to share other resources in supplying sustainable environmental friend power due to their economic benefits as compared with other resources and technologies. Energy generated from wind is growing faster than other renewable resources especially at areas with proper wind speed and characteristics capable to generate high power at small land and the possibility to interconnect wind networks with distribution or transmission power networks. Predictability of wind availability and characteristics is limited; therefore, the output of wind turbines cannot be controlled to the same extent as conventional generation technologies. This study involves assessing the impact of interconnecting a 50 MW wind plant at different penetration levels into a 132-kV grid powering a region in the sultanate of Oman isolated (islanded) from the main national grid. The assessment includes mutual impacts on power quality and flow, grid voltage flickering and performance of the network and the farm under steady state and disturbance conditions. The wind plant is constructed from an 18-equal capacity DFIG wind turbines modelled using the simulation from MATLAB/Simulink available in the college. Parameters of control and operation parameters were developed to fit the wind plant operating conditions. The penetration levels considered in the research include 1, 9 & 18 wind turbines in operation respectively which represent 5.5 %, 50 % and 100 % of the maximum farm generation capacity. The research outcomes revealed that penetrating the wind plant at the levels mentioned above provide high accuracy of compliance with the national and international standards and codes and that it shall not conflict the requirements of power quality and security of supply restricted in grid code and regulations. The outcomes obtained also provide high degree of confidence for integrating the wind plant with the existing grid network at the proposed point of common connection (PCC) without any additional extra works required on the existing network rather than those required for adaptation requirements.

ABSTRAK

Permintaan untuk tenaga elektrik terus berkembang disebabkan oleh perkembangan dalam parameter makro-ekonomi masyarakat; Penduduk dan Keluaran Dalam Negara Kasar (KDNK). Pada masa ini, elektrik terutamanya dijana daripada sumber konvensional termasuk bahan api fosil (minyak, arang batu, gas, dan lain-lain) dan bahan api nuklear. Peningkatan permintaan meningkatkan kebimbangan mengenai kekurangan bahan api fosil, meningkatkan karbon dioksida (CO₂) dan pelepasan lain, pencemaran alam sekitar dan perubahan iklim. agensi tenaga global digesa mencari sumber-sumber rakan lestari dan alam sekitar. sumber tenaga boleh diperbaharui terutama angin dan sumber solar terdapat sumber bercita-cita tinggi yang boleh dibangunkan untuk berkongsi sumber-sumber lain dalam membekalkan mampan kuasa rakan alam sekitar kerana manfaat ekonomi mereka berbanding dengan sumber-sumber dan teknologi lain. Tenaga yang dijana daripada angin berkembang lebih cepat daripada sumber boleh diperbaharui yang lain terutama di kawasan dengan kelajuan angin yang betul dan ciri-ciri yang mampu untuk menjana kuasa tinggi pada tanah yang kecil dan kemungkinan untuk saling rangkaian angin dengan rangkaian pengedaran atau penghantaran kuasa. Kebolehamalan ketersediaan angin dan ciri-ciri adalah terhad; oleh itu, output turbin angin tidak boleh dikawal ke tahap yang sama seperti teknologi penjanaan konvensional. Kajian ini melibatkan penilaian impak bersambung ladang angin 50 MW ke dalam grid 132 kV menjanakan kawasan yang dalam kesultanan Oman diasingkan daripada grid nasional utama pada tahap penembusan yang berbeza. Penilaian ini merangkumi kesan bersama mengenai kualiti kuasa dan aliran, kelipan voltan grid dan prestasi rangkaian dan ladang di bawah keadaan dan gangguan stabil. Ladang angin dibina daripada 18-sama turbin angin kapasiti DFIG dimodelkan menggunakan simulasi dari MATLAB / Simulink tersedia di kolej. Parameter kawalan dan operasi parameter telah dibangunkan untuk memenuhi syarat-syarat operasi ladang angin. Tahap penembusan dipertimbangkan dalam kajian ini, terdapat 5.5%, 50% dan 100% daripada kapasiti penjanaan ladang maksimum. Hasil penyelidikan menunjukkan bahawa menembusi ladang angin di peringkat yang dinyatakan di atas menyediakan ketepatan yang tinggi pematuhan dengan piawaian dan kod negara dan antarabangsa dan bahawa ia tidak boleh bercanggah keperluan kualiti kuasa dan keselamatan bekalan terhad kod dan peraturan grid. Hasil yang diperolehi juga menyediakan tahap keyakinan yang tinggi untuk mengintegrasikan ladang angin dengan rangkaian grid yang sedia ada pada ketika cadangan sambungan biasa (PCC) tanpa apa-apa kerja tambahan tambahan yang diperlukan di dalam sistem sedia ada dan bukannya yang diperlukan untuk keperluan penyesuaian.

ACKNOWLEDGEMENTS

First and foremost, I would like to take this opportunity to express my sincere acknowledgement to my supervisor Associate Professor. IR. Dr. Rosli Bin Omar from the Faculty of Electrical Engineering Universiti Teknikal Malaysia Melaka (UTeM) for his essential supervision, support and encouragement towards the completion of this dissertation. Secondly, I would also like to express my sincerer acknowledgment to my corresponsor Prof. Dr. Marizan bin Sulaiman from Research and Innovation Center (CRetia) for his guide and support toward completing the study.

I would also like to express my greatest gratitude to Dr. Adeal Al-busaidi planning manager at Oman Electrical Transmission Company (OETCO), co-supervisor of this project for his advice and suggestions in evaluation of data gathering and his approval to investigate the control model on the current power plant. Special thanks to UTeM short term grant funding for the financial support throughout this project. Also, I need to extend my thank to Rural Area Electricity Company for their helping in visiting the plant and do the possible and maximum help to test the proposed model of penetration level indicator.

Particularly, I would also like to express my deepest gratitude to ENG. Salam Mohammed Ahmed research and development section head and the planning engineers from planning section Rural Area Electricity Company (RAECO),

Special thanks to all my peers, my late mother, beloved father and siblings for their moral support in completing this degree. Lastly, thank you to everyone who had been to the crucial parts of realization of this project.

TABLE OF CONTENTS

	PAGE
DECLARATION	
APPROVAL	
DEDICATION	
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	viii
LIST OF FIGURES	viii
LIST OF ABBREVIATION	xii
LIST OF PUBLICATIONS	xvii
CHAPTER	
1. INTRODUCTION	1
1.1 Overview of Renewable Energy	1
1.2 Motivation of the Research.	6
1.3 Problem Statement	7
1.4 Objective of Research	8
1.5 Contribution of the Research	9
1.6 Scope of the Research	9
1.7 Organization of Dissertation	11
2. LITERATURE REVIEW AND THEORETICAL ANALYSIS	13
2.1 Introduction	13
2.1.1 Wind Power in Power Systems:	13
2.1.2 Wind Power System	16
2.1.3 Power Generation from Wind	18
2.2 Induction Generators	20
2.2.1 Variable Speed Turbines	22
2.2.2 Classification of Wind Turbines	24
2.3 Double Feed Induction Generator (DFIG)	26
2.4 DFIG wind Turbine Modeling	30
2.4.1 Wind Turbine Modelling	31
2.4.2 Gear Box Modelling	33
2.4.3 Generator modeling	34
2.4.4 Power Converter models	39
2.5 Control Methods	40
2.6 Turbine Blade Aerodynamics	44
2.7 Steady-state operation and control of the DFIG	46
2.8 Back to Back Convertor	50
2.8.1 Rotor power converters	50
2.8.2 The Grid-Side Converter (GSC)	52
2.9 Protecting the DFIG	54
2.9.1 Braking Systems	55
2.9.2 Converter Protection Systems	55
2.10 Issues for Integration Wind Power into Grid Networks	56

2.10.1	Voltage Variations	59
2.10.2	Voltage fluctuations (Flickering)	61
2.10.3	Continuous operations - flicker coefficient	63
2.10.4	Switching Operations	63
2.11	Harmonics	64
2.12	Frequency control	64
2.13	Transient Stability	66
2.14	Small Signal Stability	66
2.15	Fault Ride through Capability	66
2.16	Electrical Grid Simulation	68
2.17	Modeling of wind plants:	69
2.17.1	Individual wind plant Modeling	69
2.17.2	Reduced Modeling of Wind plant:	70
2.18	Summary of chapter 2:	71
3.	METHODOLOGY	73
3.1	Introduction.	73
3.2	System modelling system developed without wind plant	76
3.2.1	Description and Information of Existing System under Study	76
3.2.2	System development for interlinking with the wind plant	78
3.3	System modeling with wind plant	82
3.4	Modeling of DFIG wind Turbines Used:	85
3.5	Performance validation of the DFIG Turbine and the WP.	89
3.5.1	Adjusting reactive power withdrawn using Capacitor bank.	92
3.5.2	Output validation of single GE 2.75 -120 DFIG and Total WP output.	95
3.5.3	Validation of Control system Performance	96
3.5.4	Validation of WP Protection Performance	97
3.5.5	Mode of Operation Performance	98
3.6	Summary of chapter	104
4.	RESULT AND DISSCUSSION	102
4.1	System analyses without interconnection with the wind plant	102
4.1.1	Summary of Loaf flow from Matlab/Simulink	102
4.1.2	Dynamic Performance of System	103
4.2	Results Associated with Penetration Level Effect	104
4.2.1	Case 1: Penetrating 1x2.78 MW wind power into the grid	105
4.2.2	Case 2 : Penetrating 9x2.78 MW wind power into the grid	107
4.2.3	Case 3 : Penetrating 18x2.78 MW wind power into the grid	109
4.3	Power Quality Measurements	110
4.3.1	Continous Operation Voltage Flickering	110
4.3.2	Voltage flickering through WP Switching ON:	112
4.3.3	Voltage flickering through WP Switching OFF and then ON	114
4.4	Stability Measurements	115
4.4.1	Samll Load disturbance	115
4.4.2	Fault disturbanc	116
4.5	Low Voltage Ride through (LVRT) Capability	117
4.6	Summary and Conclusions of chapter 4	119

5. CONCLUSION AND FUTURE WORK	121
5.1 Conclusions	121
5.2 Achievement of Research Objectives	122
5.3 Significance of Research Outcomes	123
5.4 Recommendations and Future Works	124
REFERENCES	126
APPENDICES	136

LIST OF TABLES

TABLE	TITLE	PAGE
3.1	Capacities of current gas fired power plants	77
3.2	132 kV underground Cables in Grid network	78
3.3:	132 kV Network existing 132 kV over head lines of network	78
3.4.	132 kV Grid bus loads	82
3.5:	Characteristic of the GE 2.75 -120 wind turbine.	87
3.6:	Generator parameters	87
3.7	Converter parameters	87
3.8:	Turbine Parameters	87
3.9.	Protection and control parameter	88
3.10.	Comparison of computational time as per system Modelling	92
4.1	Load flow analyses at 132 kV grid of loads as resulted	103
4.2.	Rated power flow parameters without WP (base)	119

LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	World total GDP per region (Singer & Peterson 2016)	1
1.2	World energy consumption by region, 1990–2040 (quadrillion Btu)	2
1.3	Share of world energy resources (Singer & Peterson 2016)	3
1.4:	Renewable power capacity(Kumar et al., 2016)	4
1.5:	Global cumulative installed wind capacity 2000-2015	4
1.6:	Capacity of wind with the diameter(Loos, 2015)	5
2.1:	Cumulative Global Installed wind generation Capacity	15
2.2	Wind turbine Structure	16
2.3	Wind turbine real componrnts	17
2.4	Flow of wind through swepted area of wind turbine	18
2.5	Slip curve an induction machine	20
2.6	Speed and power curve in fixed speed wind turbine	22
2.7	Speed and power characteristic for variable speed	23
2.8	Fixed speed rotor resistance induction generator	24
2.9	Variable resistance rotor induction generator	25
2.10	DFIG diagram	25
2.11	Full Converter induction generator	26
2.12	The double fed induction generator with grid	27
2.13	Power coefficient and electric power and wind speed of DFIG	29
2.14	Modelling Block diagram of DFIG wind turbine	30

2.15	Block diagram processing input wind power	31
2.16	Wind turbine characteristic(Camm et al., 2009)	32
2.17	Generator speed with toraque characteristic	33
2.18	Generator interia and interia of component.	33
2.19	Generator modelling.	34
2.20	Q and d axis characterstic	37
2.21	Equivalent circuit of generator	38
2.22	AC/DC/AC converter(Garcia and Acha, 2013).	40
2.23	Speed with power cut in, rated & cut out (Anon, 2008)	41
2.24	Block diagram of controller (Hongtao and Luguang, 2012).	42
2.25	System-level layout of a wind energy system (Anon, 2008).	43
2.26	The Yaw and pitch control(Burns, 2001)	45
2.27	controlof WT Pitch angle (Burton, 2011)	46
2.28	Steady state operation of DFIG Turbine (Electropaedia, 2010).	47
2.29	Magnetic field of the generator	48
2.30	Equivalent circuit of an induction generator (Anon, n.d.)	48
2.31	Simplified equivelent circuit of the induction machine.	49
2.32	Slip with stator,rotor and mechanical power curve.	51
2.33	Total rotor-side converter control scheme (Zou, 2015).	52
2.34	Controller diagram (Dousoky and Shoyama, 2017)	52
2.35	(a) SLD of generator-side converter at steady-state. (b) phasor diagram	53
2.36	Total stator-side converter control scheme.	54
2.37	Converter protection system	56
2.38	Power Quality.	57

2.39	Voltage variation (de Alegria et al., 2007).	59
2.40	Typical reactive power limiting curve.	60
2.41	Voltage shape under flickering (power quality, 2011)	61
2.42	Frequency profile under flickering	62
2.43	Change of the power with frequency(Ibrahim et al., 2011).	65
2.44	LVRT of the system (Suvire, 2011).	67
2.45	Electrical system simulation(Qiao et al., 2008).	68
2.46	Block diagram of a complete DFIG wind farm model.	69
2.47	Block diagram of a full aggregated (Qiao et al., 2008)	71
3.1	Flow chart of the research.	75
3.2	SLD of existing 132 kV grid network network	77
3.3	SLD of the132 kV grid network without wind farm.	80
3.4	Simulation in MATLAB/Simulink package without wind farm.	81
3.5	Layout of WP interconnected into the grid.	84
3.6	SLD of the132 kV grid network network with wind farm.	85
3.7	GE 2.75-120 Wind turbine power characteristics.	86
3.8	Protection and control parameters.	89
3.9	Simulation in MATLAB/Simulink package with wind farm.	89
3.10	System Starting without capacitor bank.	93
3.11	System Starting with 15 MVAR capacitor bank.	94
3.12	System Starting with 30 MVAR capacitor bank.	94
3.13	Power output wind speed characteristics of single	95
3.14	Power output wind speed characteristics of the wind plant	96
3.15	Validating of Pitch control with wind speed more than rated speed.	97

3.16	Examining the effect of abnormal conditions at zero pitch .	98
3.17	Validation of voltage control mode of operation	99
3.18	Validation of VAR control mode of operation.	99
4.1	Performance of the system without wind plant.	104
4.2	Performance with 1x2.78 MW penetration level at wind side	106
4.3	Performance with 1x2.78 MW penetration level at PCC side.	107
4.4	Performance with 9 x2.78 MW penetration at wind plant side	108
4.5	Performance with 9x2.78 MW penetration level at PCC side.	108
4.6	Performance with 18 x2.78 MW penetration at wind plant side	110
4.7	Performance with 18x2.78 MW penetration level at PCC side.	110
4.8	Disturbances in output at high speed when pitch angle control	111
4.9	Switching flickering of 18x2.78 MW wind power penetration	113
4.10	Voltage flickering through WP Switching ON of WP	113
4.11	Voltage flickering through WP Switching OFF and then ON	114
4.12	Small signal disturbance on wind plant terminal.	115
4.13	Introduces the output profile of measurements	116
4.14	Impact of fault disturbance on output from 18x2.78 MW	117
4.15	Low Voltage Ride Through (LVRT) on 18x2.78 MW wind	118

LIST OF ABBREVIATION

ρ	Air density
Λ	Tip Speed Ratio
Ω_r	Rotor Angular Speed
A	Cross-Sectional Area of the Wind That Crossed the Blades
AC	Alternating Current
ASG AA	Synchronous Generator
ANSI	American Nation Standard Institution
β°	Blade Pitch Angle
CO ₂	Carbon Dioxide
C _p	Power Coefficient
C _{grid}	Convertor Grid
C _{rotor}	Convertor Rotor
D-axis	Direct Axis
DC	Direct Current
DFIG	Double Fed Induction Generator
EIA	Energy Information Administration
EMF	Electro Motive Force
FRT	Fault Ride Through
GC	Grid Code
GDP	Gross Domestic Product

GE	General Electric
GSC	Grid-Side Converter
GWEC	Global Wind Energy Council
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Isolated Gate Bipolar Transistor
IPP	Independent Power Plant
IRENA	International Renewable Energy Agency
KE	Kinetic Energy
kV	Kilo Volt
kVAR	Kilo Volt Ampere Reactive
kWh	Kilo watt hour
kW	Kilo Watt
LVRT	Low Voltage Ride Through
LOL	Line to Line
MW	Mega Watt
MPPT	Maximum Power Point Tracking
OECD	Organization for Economic Co-operation and Development
OETC	Oman Electricity Transmission Company
OHL	Over Head Line
PCC	Point of Common Connection
P _{gc}	C grid electrical power output
PI	Proportional – Integral
P _m	Mechanical power captured by the wind turbine and transmitted to th rotor.
P _r	Rotor electrical power output

Ps	Stator electrical power output
PWM	Pulse Width Modulation
PU	Per Unit
Qs	Stator reactive power output
Qr	Rotor reactive power output
Qgc	Cgrid reactive power output
Q-axis	Quadrature axis
Rpm	Revolutions per minute
RLC	Resistor Inductance Capacitance
RMS	Root Mean Square
RSC	Rotor-Side Converter
RSC	Short circuit factor
S	Slip
SCIG	Squirrel Cage Induction Generator
SG	Synchronous Generator
SLD	Single Line Diagram
SSC	Short Circuit Apparent Power
Tx	Transformer
Tm	Mechanical torque applied to rotor
Tem	Electromagnetic torque applied to the rotor by the generator
TSO	Transmission System Operation
UGC	Under Ground Cable
VH	High Voltage
VHF	High Voltage Limit

VL	Lower Voltage
VLF	Low Voltage Limit
VSC	Voltage Source Convertor
WPGS	Wind Powered Generation Station
WPP	Wind Power Plant
WT	Wind Turbine

LIST OF PUBLICATIONS

Rosli Bin Omar, Suhaib Salam Mohammed, Mohammed Rasheed and Marizan Sulaiman., (2017). " Aggregated Modelling Analysis of power flow from Wind Power Plant into Grid System Using MATLAB/SIMULINK Software", ARPN Journal of Engineering and Applied Sciences (JEAS).

CHAPTER 1

INTRODUCTION

1.1 Overview of Renewable Energy

Globally, demand for electricity is continuously increasing due to the development in community's macro-economic parameters; Population and the Gross Domestic Product (GDP). Power demands in Organisation for Economic Co-operation and Development (OECD) grow slower than those in non OECD members, since they demonstrate more increase in populations, GDP, and the industrialization activities. Figure 1.1 introduces World total gross domestic product 1990-2040 per region (Trillion 2010 US \$) , while Figure 1.2 introduces World Energy Consumption (Trillion kWh) trillion= 10^{12} (Singer and Peterson, 2016).

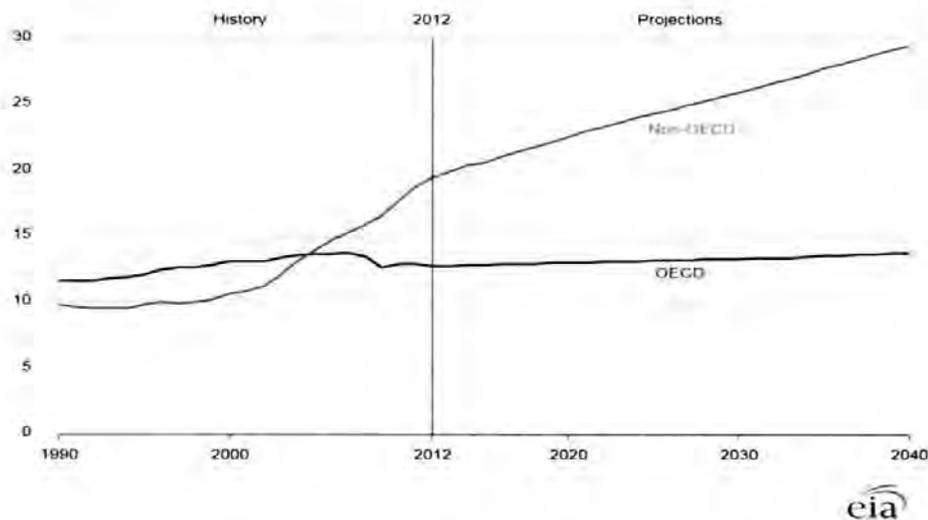


Figure 1.1: World total GDP per region (Singer & Peterson 2016)

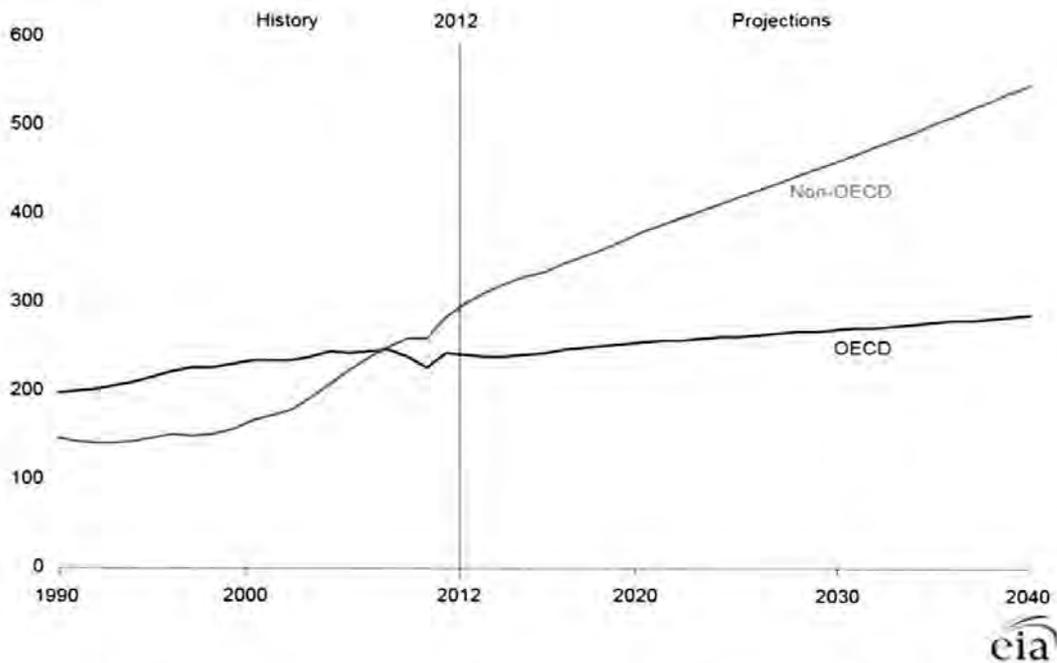


Figure 1.2: World energy consumption by region, 1990–2040 (quadrillion Btu) (Singer & Peterson 2016).

In consistent with the growth in demand at the required quality and security, complexity of electric power systems has evolved to meet the requirements of supply. Electric power is generated from different energy resources which are classified into two main categories, non-renewable and renewable energy resources. Non-renewable (conventional) sources are divided into two types; fossil fuels (oil, coal, gas, etc.) and nuclear fuel. Solar and wind are the main renewable energy resources. At present electric power is mainly generated from non-renewable resources as shown Figure 1.3.

Therefore, increase demand for electricity depends largely on fossil fuels with minors from hydro power and nuclear energy. The increase in fossil fuel consumption increases the concerns about carbon dioxide (CO₂) emissions, environmental pollution, and climate changes. Renewable sources are big sources of energy, mainly from sun, wind, and seas, but the challenge is how to harnessing them. Recently more technological advance achievements have been developed to increasing the share of renewable resources in the

deal of energy supplied. Different sources of renewable energy share the supply of energy to consumers. Including solar Energy, photovoltaic Systems, solar hot water, Solar Electricity, wind, Geothermal Energy, Geothermal Electricity Production, Bioenergy, Biofuels, Hydropower, Ocean Energy, Hydrogen & Fuel Cells.

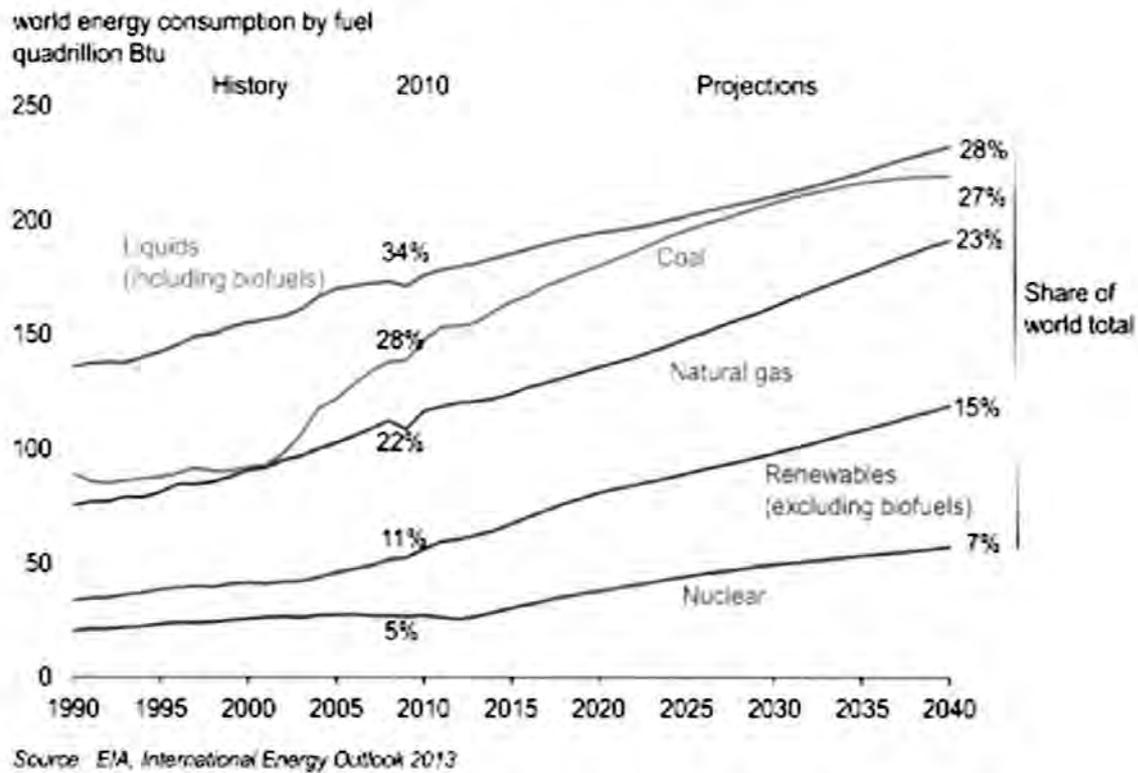


Figure 1.3: Share of world energy resources (Singer & Peterson 2016)

*(quadrillion) 10^{15} BTU, or 1.055×10^{18} joules

Demonstrates that solar and wind sources of power show significant increase in installed power capacity and it is expected to grow more as cost of energy shows more trend to reduction and it becomes competent to other conventional sources of energy and even lower Figure 1.4 Global Cumulative Installed Capacity 2000-2015(Badihi et al., 2015)(Mishra and Chowdhury, 2015).