A THESIS

FOR THE DEGREE OF MASTER OF ENGINEERING

Analysis of Levelized Cost of Energy for Wind Farm in Operation on Jeju Island, South Korea

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Abstract

All of countries are attempting to work on global climate change with explicit goals and effort into new and renewable energy instead of sticking with conventional energy. It is notable that wind power generation has lower CO_2 emission among renewable energy. According to NEA (Nuclear Energy Agency), Levelized Cost of Energy (LCOE) for onshore wind power would become equal or lower than other conventional energy except nuclear energy from 2020. In order to describe and compare the fundamental economics with other countries and to estimate representative Levelized Cost of Energy (LCOE) for onshore wind power for South Korea LCOE was calculated and analysed based on actual data from a wind farm in operation. This is the first time to calculate and analyse LCOE for wind power in South Korea while there are already some of studies and researches have been released for LCOE for photovoltaics.

It is essential for financial investors to conduct a preliminary feasibility study including wind resource measurement of a potential wind farm development to evaluate economic efficiency as well as wind farm efficiency, and determine whether investment should be made or not. In order for this purpose to be feasible, LCOE should be calculated with consideration of all of the costs such as CAPEX and OPEX over the project lifetime. Data such as CAPEX, OPEX, and AEP used in this thesis is real data from AB wind farm located Jeju Island, South Korea. As data was only available from 2012 to 2015 from AB wind farm, LCOE was only calculated and averaged for available years and estimated representative LCOE for South Korea. The same amount of CAPEX was applied to respective years since it is one time cost incurred during wind farm construction but OPEX varied especially with unscheduled service in each year. It was found that low wind speed substantially impacted on AEP and capacity factor which eventually impacted on LCOE.

As a result the range of LCOE values of AB wind farm are 0.096$/kWh ~ 0.118$/kWh which are slightly higher range values than other countries. OPEX range of AB wind farm is from $1,213,645 to $2,414,322 and the average OPEX is $1,718,786 which is equal to 52,084$/MW/yr. The total OPEX includes average 60% of wind turbine O&M costs, which is average 31,251$/MW/yr, paid to contractor (wind turbine manufacturer) as warranty contract payment and 40% of scheduled

costs such as land lease, insurance, utility bill, labor management, and support fund for local society and so on of which average scheduled costs are 20,833$/MW/yr. CAPEX of AB wind farm is $59,329,998 which is equal to 1,797,879$/MW, which was similar to that of other countries except wind turbine cost that varied by countries.

초록

현재까지 국내에서는 실제 가동중인 풍력발전단지의 데이터를 이용하여 각 년도 별 에너지균등화비용을 계산하고 분석하여 풍력발전기를 통해 생산된 전력의 가격경쟁력을 확인해본 사례가 없기 때문에 현재 가동중인 풍력발전단지의 데이터를 이용하여 에너지균등화비용을 계산 및 분석하여 향후 해당 풍력발전단지의 에너지균등화비용을 예측하고 예측된 값을 바탕으로 국내의 풍력발전 에너지균등화비용 수준도 같이 예측해 보았다. 풍력에너지는 신재생에너지 중에서도 시간 당 메가 와트(Megawatt-hour)대비 이산화탄소 배출이 가장 낮게 나타나고 있다. 또한 NEA(Nuclear Energy Agency)에서 발표한 자료에 따르면 2020 년까지 상업운전을 시작하는 약 181 개의 기존 발전소 (석탄, 원자력 등)들의 전력생산대비 발전단가 즉 에너지균등화비용(Levelized Cost of Energy)을 비교한 결과 2020 년 기준으로 육상풍력의 경우 에너지균등화비용이 기존 발전소에 비해 비슷하거나 낮을 것으로 전망되고 있다.

풍력발전단지 조성 전 예비타당성 조사를 실시하여 해당 풍력발전단지의 경제성을 예측하고 그 결과를 통하여 투자여부를 결정하는 게 재무투자자들의 일반적인 절차이다. 하지만 풍력발전단지 조성 후 총 투자비, 운영비 및 기타 비용 대비 전력생산단가를 계산하여 생산되는 풍력에너지의 가격경쟁력을 가늠할 수 있는 지표가 국내에는 현재 부재 하다. 이에 반해 미국신재생에너지연구소인 NREL(National Renewable Energy Laboratory)등 에서는 매해 정기적으로 상업중인 프로젝트의 데이터 및 자체 계산모듈을 이용하여 미국시장에서의 육상풍력과 해상풍력의 에너지균등화비용을 조사하여 에너지균등화비용의 트랜드와 해당 요인들에 대한 데이터를 제공하고 있다. 이는 에너지균등화비용을 통해 기본적인 풍력발전기를 구성하는 주요부품들의 가격뿐만이 아니라 풍력에너지에 대한 전체적인 통찰력과 정보를 제공하기 위함이다.

에너지균등화비용은 해당발전단지의 총비용(설계, 건설, 유지보수 및 기타 자본비용)을 총 발전량으로 나눈 값으로 시간 당 킬로와트(Kilowatt-hour)로 발전원가를 나타내는 지표로서 해당발전단지에서 생산된 전력의 가격경쟁력을 쉽게 판단할 수 있는 투자결정의 도구로서 사업성을 손쉽게 가늠할 수 있다.

신뢰할 수 있는 에너지균등화비용을 계산하기 위해 현재 가동중인 풍력발전단지의 실제 풍력발전기 기자재 비용, 운송 설치 비용 등을 포함하는 Capital expenditure(CAPEX), 풍력발전단지 운영비에 해당하는 Operating expenditure(OPEX) 및 풍력발전기의 발전량 등은 실제 풍력발전단지의 데이터를 그대로 적용하였고, 할인율(Discount rate)은 국내 수준에 맞춰 5.5%를 적용하였다. 풍력발전단지의 2012 년부터 2015 년까지의

운영데이터를 사용하여 각 년도 별 데이터를 계산하였고, 이들 값의 평균값으로 해당 풍력발전단지의 에너지균등화비용을 예측하였다. 또한 해당 풍력발전단지의 에너지균등화비용 결과 값과 해외에서 제시하는 지표 값을 비교하여 국내 풍력발전사업의 경제성도 같이 분석해 보았다.

이에 대한 결과로 해당풍력발전단지의 2012 년부터 2015 년까지의 LCOE 는 0.096$/kWh ~ 0.118$/kWh 으로 나타났고 이에 대한 평균 LCOE 는 0.1035$/kWh 로 나타났다. 이는 해외에서 제시하는 각 나라별 지표 값보다 높은 값이지만 에너지경제연구원(KEEI)에서 제시한 2016 년 LCOE (0.117$/kWh)와 해당풍력발전단지의 2015 년 LCOE(0.118/kWh)가 같은 수준이므로 풍력발전기 유지보수를 제조사에서 진행하는 조건의 국내 풍력발전단지의 LCOE 는 같은 수준일 것으로 예측할 수 있다. 가동 년도의 평균 OPEX 비용은 $1,718,786 로 해외에서 제시하는 각 나라별 지표 값보다는 많이 높게 나타나고 있으나, 총 OPEX 비용 중 60%에 달하는 풍력발전기 유지보수에 따른 Warranty contract payment 가 포함된 조건에서의 OPEX 값이기 때문에 다른 나라와 똑같이 warranty contract payment 조건이 적용되지 않을 경우 비슷한 수준으로 예측된다.

총 CAPEX 비용는 $59,329,998 이며 이중 풍력발전기 기자재 비용은 약 77%를 차지한다. 나라 별로 풍력발전기 기자재 비용이 조금씩 상이하기 때문에 순수하게 CAPEX 비용만 비교했을 경우 다른 나라의 지표와 조금 높은 수준으로 예측 된다.

해당풍력발전단지의 해당 년도 별 평균풍속은 예비타당성 조사 시에 예측된 평균풍속 보다 낮은 수준으로 확인 되었으며 감소된 평균풍속으로 인해 연간출력량 및 이용률 뿐만 아니라 결과적으로는 LCOE 까지 영향을 미친 것으로 나타나고 있다. 이는 예비타당성 조사 시에 실시하는 풍황데이터 조사 및 분석의 중요성을 보여주고 있을 뿐만 아니라 LCOE 가 복합적인 요소들에 의해 변동 될 수 있다는 것을 보여주고 있다.

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List of Acronyms

kWh	Kilowatt hour
MWh	Megawatt hour
GWh	Gigawatt hour
LCOE	Levelized Cost of Energy
CAEPX	Capital expenditure
OPEX	Operating expenditure
AEP	Annual energy production
BoP	Balance of Plant
TIC	Total installed cost
O&M	Operation and Maintenance
GIS	Gas-insulated switchgear
NPV	Net present value
PPA	Power purchase agreement
REC	Renewable energy certificate
FIT	Feed in Tariff
SMP	System marginal price
a.g.l	Above ground level
MAA	Measured average availability
WAA	Warranted average availability
NREL	National renewable energy laboratory
NEA	Nuclear Energy Agency
IEA	International energy agency
EWEA	European wind energy association
KEEI	Korea energy economics institute
PV	Photovoltaics
WT	Wind turbine

1. INTRODUCTION

1.1 Background

Wind power as a part of renewable energy has been growing up in South Korea thanks to predefine government target so called green growth despite of unfavourable conditions in small geographic size and limited wind power restraining from development of wind farms. Wind industry is small compared to other countries but accumulated wind power at the end of 2015 is 804MW and 184MW capacity of wind turbines will be installed in 2016, which will bring the total installed capacity is nearly 1GW soon [7] .

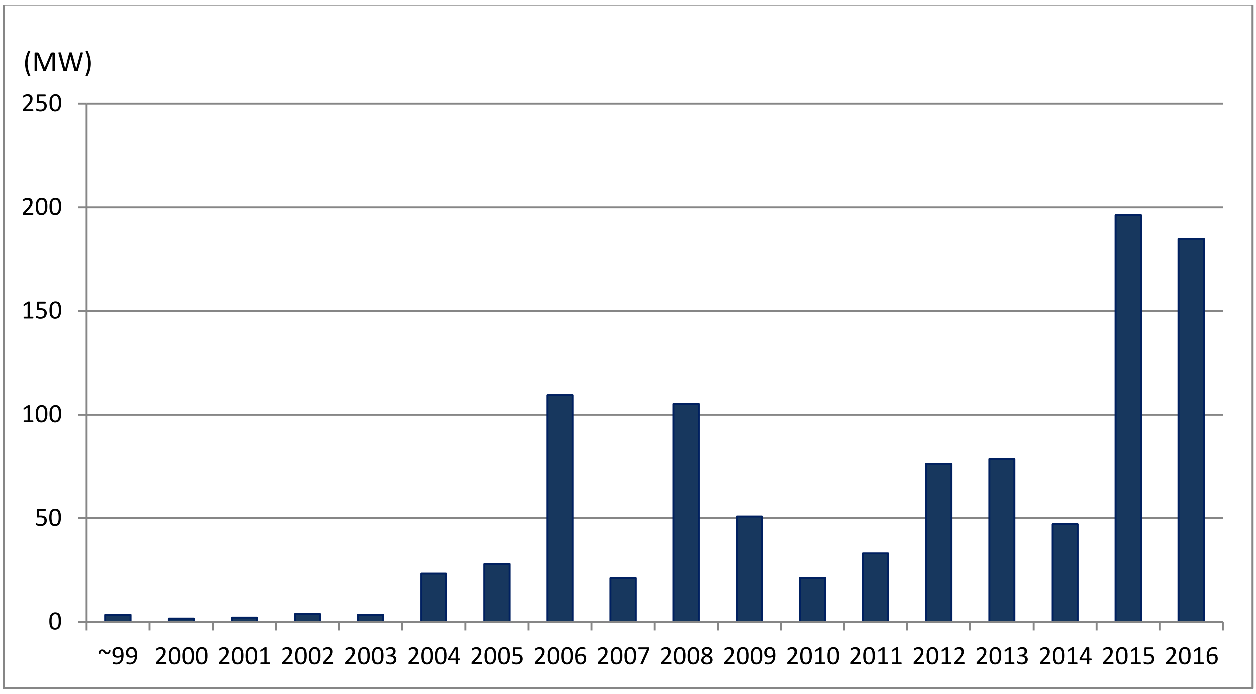

Figure 1: Installed wind power capacity from 1999 to 2016 in South Korea

Wind power is environment-friendly and cost effective compared to other renewable energy [2] . Wind power is the cheapest resources and the cost of electricity production by wind is much more competitive than conventional energy such as fossil fuel based electricity production. However there has been not many information or study about evaluating and estimating wind generation costs, which can be done based on levelized average lifetime cost approach [2] using LCOE equation, for Korean wind power sector whereas there are already several researches and studies discussing and estimating LCOE for Korean solar PV market sectors. Thus there is none of real data and information available in Korea market for wind power as reference to estimate energy costs (LCOE) and to make a decision whether to carry out the project or make an investment based on estimated energy cost (LCOE) even though the first commercial wind farm was built back in the early 1990s. On the other hand energy laboratories and agencies such as EWEA, NREL, IEA, NEA [2], [4], [8], [11] in other countries have been issued reports periodically to maintain wind generation cost trends and their drivers for the stakeholders such as project developer, wind farm operator, financial institutions, and OEMs, etc. Therefore calculating and analysing LCOE together with CAPEX and OPEX for Korea wind power market was carried out.

1.2 Objective

The main purpose of this thesis is to calculate and analyze LCOE based on the data from 33MW capacity of wind farm located in Jeju Island, South Korea and to help understanding of wind generation costs and their drivers. This is also intended to provide insight in estimating current and future LCOE for Korean market for the assessment of average lifetime costs providing as either dollars per kilowatt-hour($/kWh) or dollars per megawatt-hour($/MWh) for the production. In order to achieve this objective wind farm visit was made to ascertain all of real data and factors which are required to calculate LCOE.

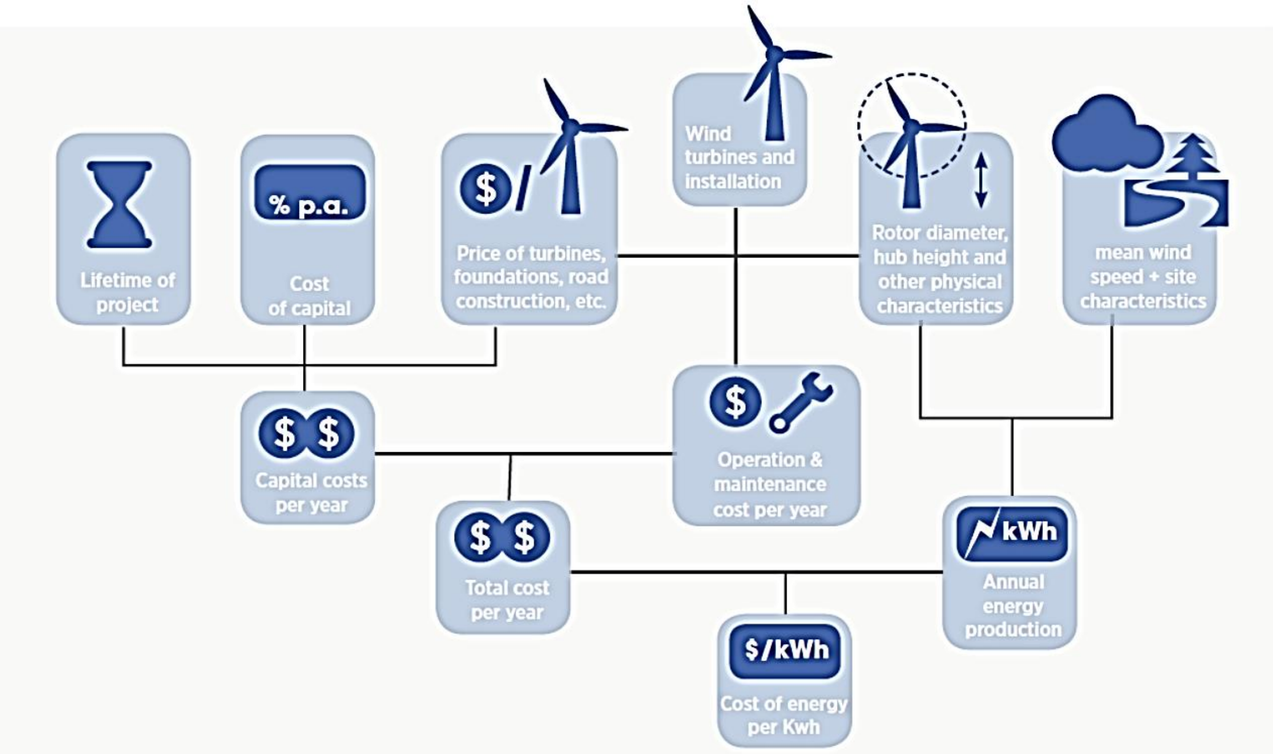

Figure 2: Cost of energy for a wind farm

Cost of energy for wind power is subject to projects and wind farms specific characteristics and that in specific wind farms input data but standard methodology that includes basic inputs of CAPEX, OPEX, AEP, and discount rate is the same. So localized CAPEX, OPEX and cost factors as stated in Figure 2 will be also reviewed and compared with the data from other countries to review the trends and difference in specific cost drivers. Overall thesis is not only to describe the methodology of LCOE calculation but also to calculate current LCOE based on data and estimates from a wind farm in operation. As a result the estimation of reasonable or recommendable LCOE for Korea wind power which will definitely help especially developers and operator compare and select the optimal wind turbine and its technologies. This will also help make optimized decision making for final investment decision.

2. GLOBAL TRENDS IN CAPTITAL EXPENDITURE AND OPERATING EXPENDITURE

2.1 Capital expenditure (CAPEX)

CAPEX costs basically represent the total costs of constructing a wind farm or a plant but it does not include escalation costs because they can vary with country inflation and other factors. CAPEX is derived from real projects and this is well known that main contributor to CAPEX is wind turbine composed of main components of nacelle, rotor, and tower, etc. CAPEX is simply divided into following elements of wind farm project, wind turbine, foundation, electrical, and wind turbine installation, etc. but transportation costs also can cause CAPEX to increase and it is basically dependent on site location. NREL annually publish the breakdown of CAPEX for the NREL onshore reference project through annual report [4] . The data of cost elements used in a bottom-up model developed by NREL is based on US project site analysis and recent trends [4] . This result slightly over predicts the total cost but it can provide better accuracy in component cost and relevant components cost changes. Turbine capital cost take majority of cost parts followed by BoP capital cost and planning and miscellaneous costs. This breakdown is not a project site specific but calibrated data of average in site analysis and recent trends. Figure 3 is not just only giving better understanding of breakdown of CAPEX but the data can be used as reference of what kind of cost elements make up CAPEX.

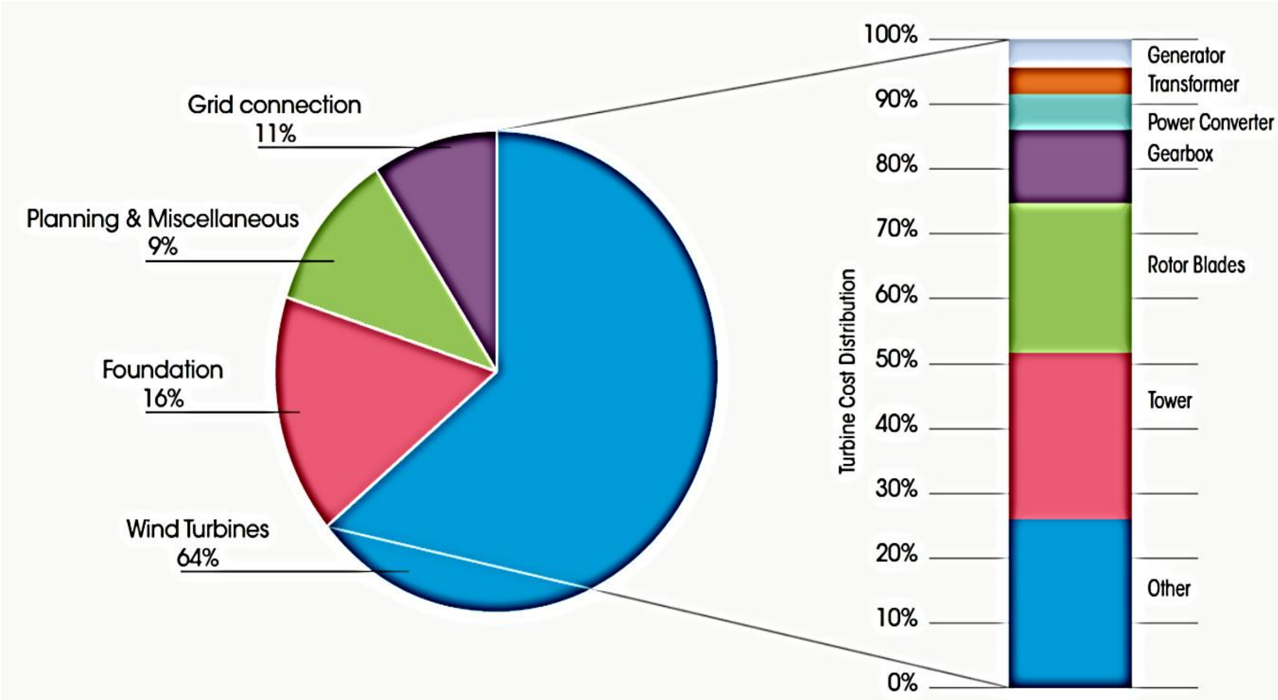

Figure 3: Breakdown of CAPEX for onshore wind farm project [20]

Main contributor to CAPEX is the cost of wind turbine. It may be as high as 70% but its proportion has been reducing from around 70% to around 62% in few years [14] . Blade and towers are priced as separate items since their price vary with their size based on the site condition especially tower size has been heightened from 80m to 100m to capture more efficient wind resource. Other costs except wind turbine costs are called BoP costs that consist of foundation costs that include erection, and civil works and grid connection that include substation, cables, control system related to grid connection.

Other costs can be separated in two classes of costs as follows. (i) Planning costs which incur prior to construction start and (ii) miscellaneous costs which incur during project construction until the project commissioning. In addition other costs also include cost of met mast in the wind farms before the project and the additional cost would be added if it has to be dismantled once the project kick off.

The percentage of reduced cost cannot be applied to all wind farm projects in the countries or be referred as representative costs for respective countries since there are countries where proportion of wind turbine cost in CAPEX has been also increased. As for increased cost of wind turbine will be explained through Figure 4.

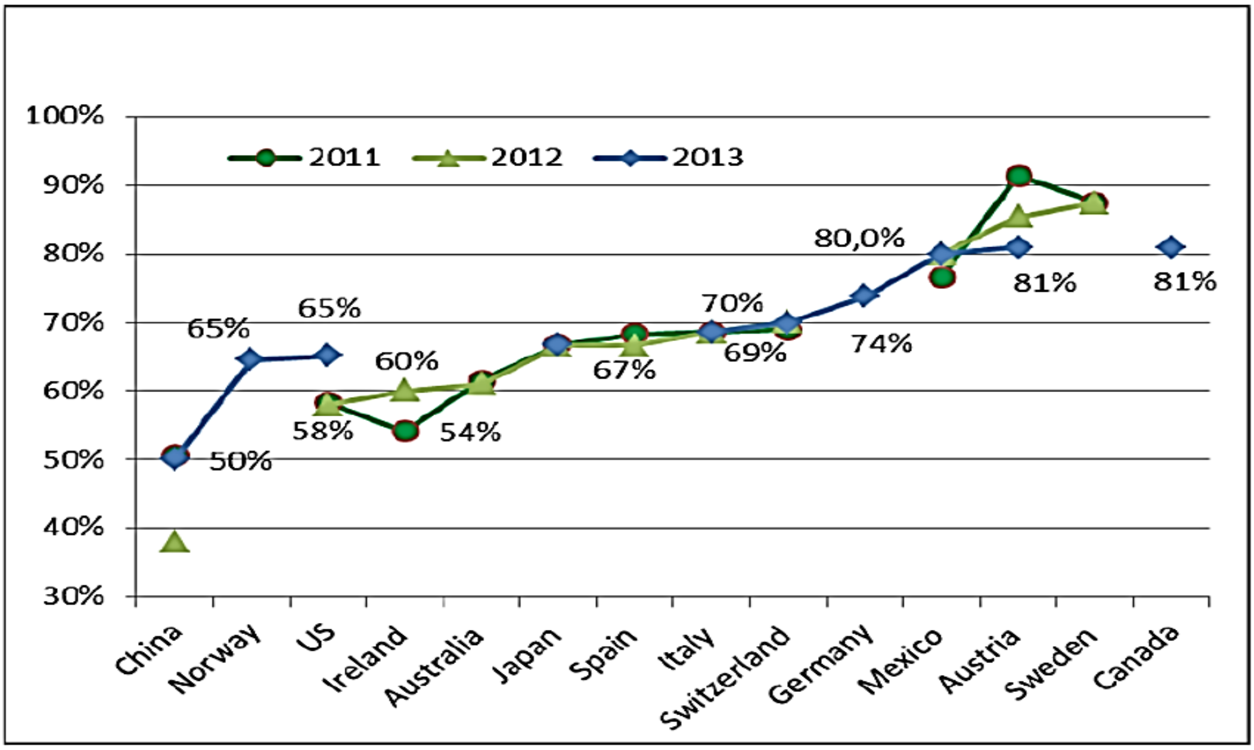

Figure 4: Wind turbine cost share of capital expenditure for onshore wind farm

Figure 4 shows different cost of wind turbine in CAPEX in respective countries. Data for China is different because they may not include foundation, tower, or electrical equipment, etc. [14] . So data for China cannot be compared with other countries. Proportion of wind turbine cost in CAPEX has been reduced clearly in Austria while there has been increased in US which may be due to larger wind turbines. As it is clearly shown proportion of wind turbine cost in CAPEX is different in all countries but wind turbine cost still has the highest proportion in CAPEX in all countries.

Table 1: Estimated average CAPEX comparison between 2012 and 2013

Country	**Turbine costs (EUR/kW (*))**		**Capital costs (EUR/kW (*))**		**Installed capacity (MW)**	
	2012	***2013***	2012	***2013***	2012	***2013***
Austria	1 430	***1 390***	1 675	***1 715***	296	***308***
China (*)	464	***480***	1 220	***960***	12 960	***16 048***
Germany onshore		***1 053***		***1 427***		***2 904***
Italy	1 200	***1 200***	1 750	***1 750***	1 273	***444***
Japan	1 740	***1 380***	2 610	***2 070***	88	***50***
Norway		***912***		***1 412***	195.5	***97.5***
Portugal		***1 080***		***1 350***		***196***
Switzerland	1 450	***1 450***	2 070	***2 070***	4	***13***
United States	853	***799***	1 470	***1 227***	13 124	***1 129***

Data missing for respective countries in Table 1 is because of lack of reliable data and different methodology but they were only included for illustration purpose [14] .

Average CAPEX for 2012 is 1,799 EUR/kW except Germany, Norway, and Portugal and average CAPEX for 2013 is 1,553 EUR/kW. As simply observed total average costs based on limited data and countries has been reduced even though wind turbine cost was increased in some of countries. This may be thanks to each innovation that impact different ranges from wind farm development, BoP, and wind turbine [17] . Therefore it is predicted a large range of innovations and maturity of the technology for onshore will reduce CAPEX in any of countries but the impact would not be big but small in CAPEX.

Table 2: Average scenario range of CAPEX for 2013

Countries	**India**	**China**	**Brazil**	**US**	**Australia**	**UK**	**France**	**Germany**
CAPEX (USDm/MW)	1.08-1.25	1.36-1.37	1.67	1.83	2.27-2.45	1.43-1.52	1.43-1.52	1.36-1.46
Countries	**Sweden**	**NL**	**DK**	**Italy**	**Spain**	**Poland**	**Romania**	**Bulgaria**
CAPEX (USDm/MW)	1.59-1.71	1.44-1.61	1.51-1.61	1.46-1.6	1.39-1.63	1.52-1.73	1.61-1.85	1.57-1.88

By means of comparing the data between Table 1 which was released from European commission [14] and Table 2 which was released from World energy council [15] , it is also anticipated that average CAPEX for the same country for the same year are similar which means CAPEX for representative countries can be used as their reference for the coming years.

2.2 Operating expenditure (OPEX)

OPEX basically consists of operation or fixed cost operation which is also known scheduled service costs, rent, tax, utilities, insurance, administration management, and other finance charge and maintenance or variable cost which include unscheduled service costs of repair either in wind turbine or in BoP for wind farm. They can be simply categorized as below.

- Operation costs – Wind farm management, administrative management, insurance, transmission, land lease, taxes
- Maintenance costs – Scheduled and unscheduled service of wind turbine and wind farm

Scheduled costs so called fixed costs are easy to compute as they are predetermined and annually incur but unscheduled cost which is also called variable costs are not easy to forecast or compute since their problem such as wind turbine break down or any of failure in BoP comes up irregularly and unexpectedly.
Table 3 [5] clearly shows the breakdown of cost elements of O&M costs. The rest not specified in the table are tax, transmission, land leases administration and management of wind farm, and other costs of which costs are more local and counties specifics compared to O&M costs.

Table 3: An example of breakdown of O&M cost categories in percentage (%)

Operation and Maintenance Costs	Proportion (%)
Labor	
Personnel	
Field salaries	14.3
Administrative	2.3
Management	5.7
Labor/personnel subtotal	22.3
Materials and services	
Vehicles	2.2
Site maintenance and miscellaneous services	0.9
Fees, licenses	0.4
Utilities	1.7
Insurance	16.6
Fuel(motor vehicle gas)	0.9
Consumables/tools and misc. supplies	5.6
Replacement parts/equipment/spare parts	49.3
Materials and service subtotal	**77.7**
Total O&M cost	**100.0**

Once project is completed manufacturers provide warranty. Warranty period for respective sites and countries are all different. However as the technology of wind turbines mature, manufacturers provide warranties that include even BoP operation which is normally operated and maintained by the operator and minimum 96% availability guaranteed performance with yield based guarantee for 5 to 10 years [14] . It is difficult to predict O&M costs with very limited data in most of countries and O&M under manufacturers' warranty and post-warranty are differently take place due to some of the issues such as spare parts, special tools, and technical issues, etc. O&M costs can be simply expressed as dollars per megawatt per year ($/MW/yr) [4] .

O&M costs have changed for onshore since 2008 [14] but O&M costs for respective countries are as stated in Table 5. It does not represent or reflect actual values but the range values given in the table are an average scenario range released from Bloomberg New Energy Finance [14] .

Table 4: Average scenario range of O&M costs for 2013

Countries	India	China	Brazil	US	Australia	UK	France	Germany
OPEX (USD/MW/yr)	10,694-24,391	17,000-25,138	24,000	24,000-24,400	33,907	28,750	20,000-22,500	19,000-21,500
Countries	**Sweden**	**NL**	**DK**	**Italy**	**Spain**	**Poland**	**Romania**	**Bulgaria**
OPEX (USD/MW/yr)	19,000-21,500	20,000-22,500	20,000-22,500	20,000-22,000	20,000-22,500	23,000-24,500	22,000-24,500	22,000-23,500

Average costs for O&M contracts have dropped 38% in the last 4 years, boosting the competitiveness significantly. This is thanks to significant improvements not only in capital costs and performance of the turbines but also in O&M costs. Average full O&M contract service excluding BoP operation and maintenance fell to EUR 19,200 MW/yr in 2012 from EUR 30,900 MW/yr in 2008 of which cumulative drop is 38% [18] . This is thanks to innovation on technically advanced wind turbine, improved BoP management, and more sophisticated siting and management of wind farms. Better planning or scheduling of O&M, more efficient and lean spare parts supply and management also helped reduce unplanned downtime which is directly related to O&M costs. As a result well organized and managed O&M has been an important resource of revenue.

OPEX including insurance, tax, land lease, administrative costs, etc can be predicted as they are recurring costs. OPEX in Table 4 does not represent each year of OPEX but the average predicted based on available data from limited wind farms. OPEX in Table 4 includes all of costs incur in operation and maintenance, so it contains uncertainty that should be considered since land lease payment for wind farms would be all different and other cost elements would be also all different in respective countries. It is difficult to predict OPEX since it can vary substantially among projects and countries but they can be used as reference and trends. OPEX has been also reduced thanks to innovation on wind turbine, BoP, Wind farm operation, and maintenance and service, etc.

2.3 Levelized Cost of Energy (LCOE)

Varieties of costs are involved with wind farms and they can be divided into several life cycle components:

- Capital cost: fixed cost of BoP consisting of construction, civil, installation, substation, grid connection and transportation, etc.
- Operating costs: fixed costs annually incurred for running wind farm

LCOE is the primary measurement to describe and compare the fundamental economic of power generation plants. For wind power, LCOE measures the sum of life cycle costs of the generation technology divided by per unit of energy produced by a wind farm [20] . LCOE is constant unit cost and is calculated over 20 to 40 years of the designed lifetime. LOCE is given in the units and it can be expressed as dollars per kilowatt hour ($/kWh) or megawatt hour ($/MWh). LCOE calculation or measurement require a number of factors to be determined [6] which can be divided into factors that determine costs and factors that determine energy production, but the main cost elements of LCOE of wind power include CAPEX, OPEX, and predicted AEP. Figure 5 simply shows the information that is required to estimate the costs and energy production for a wind farm.

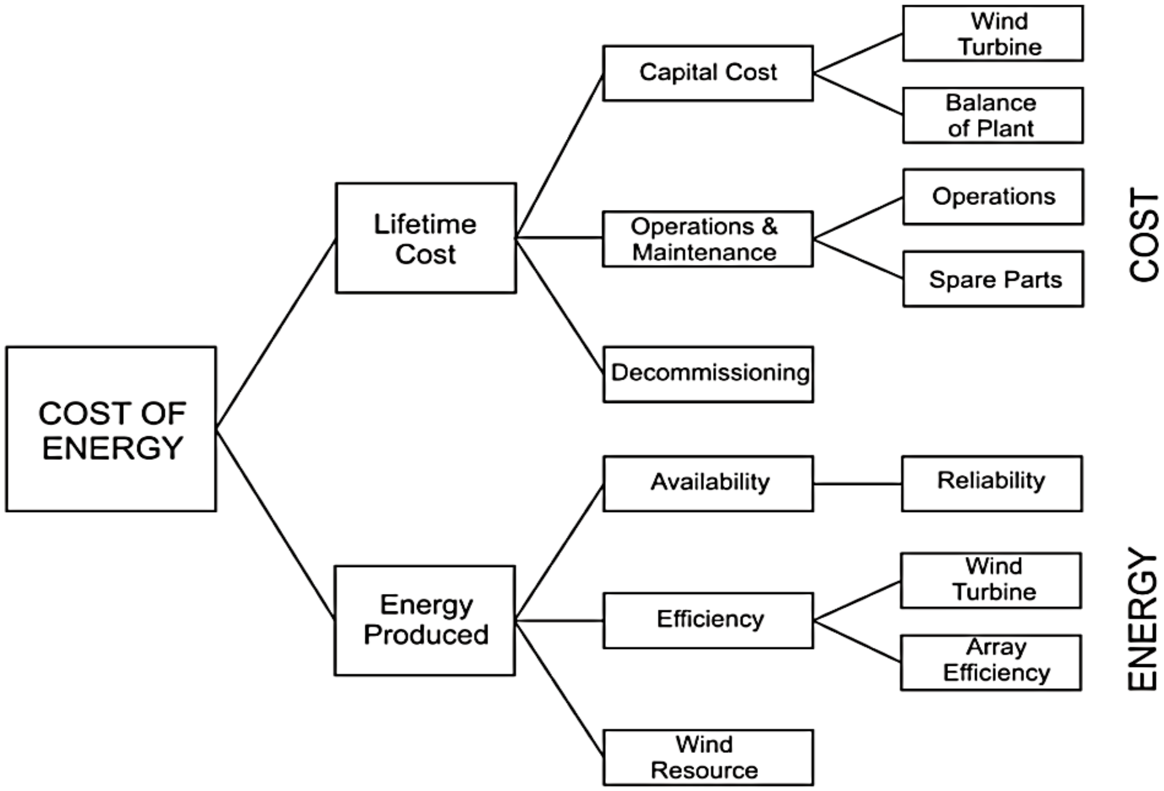

Figure 5: Breakdown of wind power economics

There are a range of variation scope in estimating LCOE, which are introduced by different use of methods, assumptions, and uncertainty. They are specified as stated in Figure 6 and they can be categorized in four [6] .

- Input data variation that arising from used scenarios, geographic locations, and timing
- Uncertainties arising from dominating financial treatments, tax rate, adjustment for risk or inflation, financial assumptions
- difference in wind turbine technology, fluctuation in material and labor costs, and wind resources
- system boundaries analyzed and whether cost categories are included or not

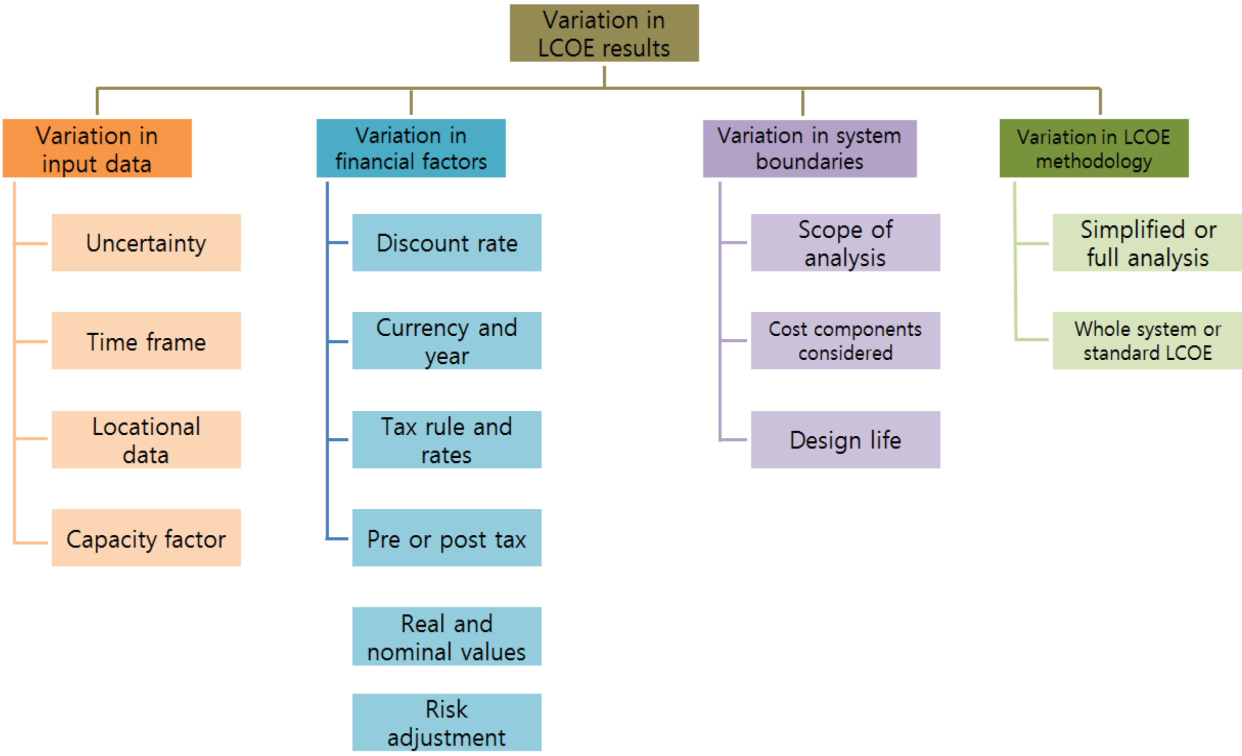

Figure: 6 Breakdown of variation in LCOE for wind farms

LCOE represents system costs in terms of the expected life time of wind farms or plants. It is calculated as the sum of discounted capital and operating costs over the generator's lifetime including sum of discounted units of electricity output. LCOE calculation can be approached with simplified LCOE calculation by:

$$LCOE = \frac{\text{Sum of costs over lifetime}}{\text{Sum of electricity produced over lifetime}}$$

If main cost elements such as investment expenditures, operation and maintenance expenditures, energy produced, discount rate, and expected lifetime are available, LCOE can be calculated as the net present value of sum of costs over the lifetime divided by sum of electricity produced over lifetime.

LCOE is the energy value that yields zero NPV [5] , that is:

$$NPV = 0 = \sum_{i=1}^{L} (LCOE\ en(i) - rc(i))/(1+r)^{i} - CAPEX \qquad (2-1)$$

Where i is the year index, L is overall life time of the project years, $en(i)$ is the total amount of energy wind turbines generated in year i, $rc(i)$ is the total recurring cost annually in year i, r is the discount rate (%), and CAPEX is the total installed cost [5] .

$$LCOE = \left(\sum_{i=1}^{L} rc(i)/\,(1+r)^{i} + CAPEX \right) / \sum_{i=1}^{L} en(i)/(1+r)^{i} \qquad (2-2)$$

In the above equation, a simplification is utilized based on the assumption that CAPEX occurs in the first year. LCOE does not depend on the equity, debt structure of the project, incentives, taxes, and other factors. When comparing LCOE of different sources of energy, the assumptions used in calculating recurring cost and discount rate must be the same.

The project would be profitable if the energy produced from the wind farm can be sold at an effective price that is greater than LCOE [5] .

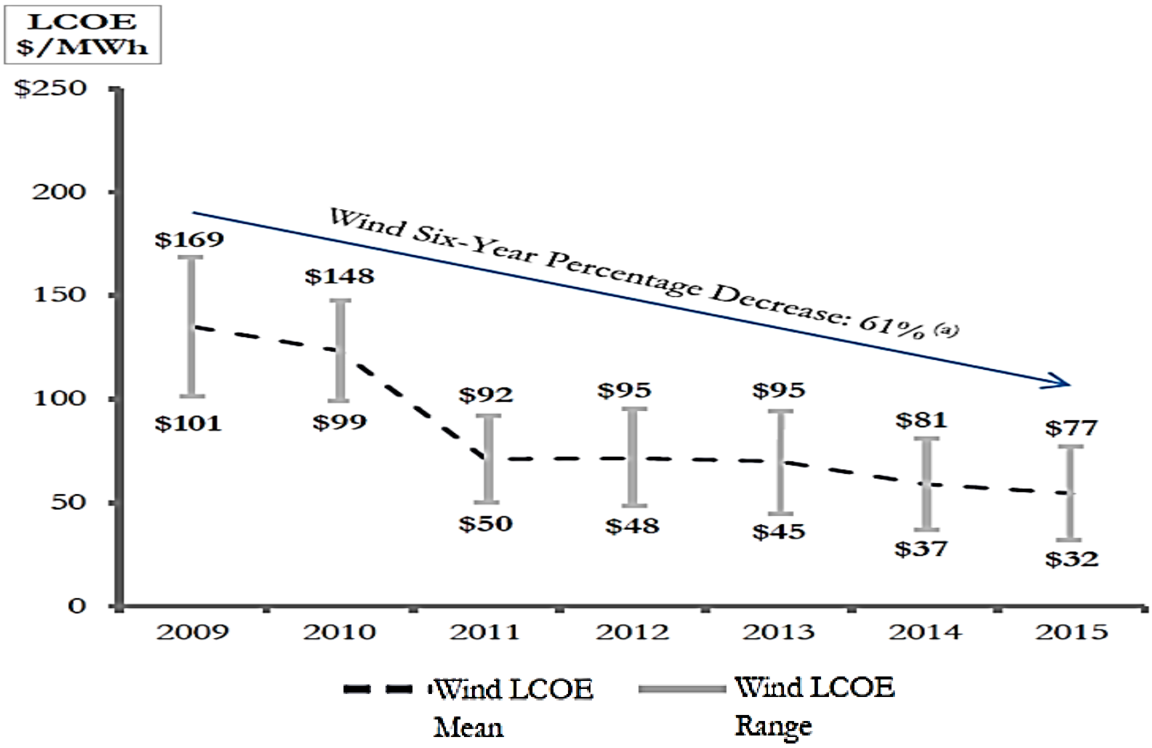

Figure 7: Wind power LCOE trends from 2009 to 2015 in U.S [21]

Wind power has become relatively competitive in cost compared to conventional generation technologies and this was thanks to many of impacts that caused substantial reduction in LCOE through innovation in the design of hardware and software, or process and technology [17] . Many of technology innovations are in development and they will cause more reduction and reliable operation and maintenance of wind farms. As a result of that wind power LCOE has been decreased as shown in Figure 7 [21] . It represents average percentage of decrease from high and low end of LCOE. The main reason of decrease in LCOE is thanks to material decline in wind turbine price and substantial improvement in efficiency and technology among other factors according to LAZARDS [21] .

It only represents U.S. but the trend of decreasing LCOE also can represent other countries as the trends in turbine cost and improvement in technology and system efficiency are the same factors that made wind power competitive and sustainable.

3. ANALYSIS OF LEVELIZED COST OF ENERGY FROM WIN FARM

3.1 Location of the site and regional description

Figure 8: Location of the AB wind farm for this study

The site is located in the east of Jeju Island, South Korea. It is approximately 6 km from the site to the sea in the south direction. The site is relatively flat with average elevation of 136m above sea level. The main vegetation on the site is high grass with a few dispersed trees and bushes. Several small rounded hills near the site are covered with dense pine trees.

3.2 Wind farm present condition

Wind farm has started running since Oct. 2009 and the site has been under warranty by wind turbine manufacturer.

Specific information about wind farm is as follows:

- Rated capacity of the wind farm: 33MW / IEC 1A wind turbine
- Wind farm area: 29,146 ㎡
- Transmission line: 8 km of 154KV Grid connecting from site substation to the substation / 5 km of 22.9KV transmission line from site substation to each turbine
- Manpower at the site: A site manager from the owner of the wind farm and three technicians from the manufacturer.
- Estimated AEP is 84.9 GWh/year
- 96% of available guarantee by manufacturer including main components such as blade, transformer, gearbox, and generator.
- Wind farm owner only operate and maintain wind farm and BoP.

3.3 Estimation of levelized cost of energy for 20 years of wind farm operation

Preliminary wind resource assessment based on initial data from the onsite measurement mast was conduct for AB wind farm located in Jeju Island, South. The final report of this preliminary assessment, which includes an evaluation of the site specific wind climatology and a wind farm energy generation as well as a financial analysis, was created. The purpose of estimating LCOE for 20years, which is wind turbine lift time, of wind farm operation is to compare LCOE before and after the wind farm project commissioned and to analyze variation in LCOE.

The result of the final report of the assessment presents the production estimate for AB wind farm. The production estimate includes array losses due to shadowing effect (wake effects) from one turbine to another within the wind farm if there is any. Electrical and availability losses have not been included in the calculation according to wind farm owner.

Based on the available information, the following results have been derived:

Table 5: The major results estimated by feasibility study for AB wind farm

AB wind farm estimated data	
Total installed capacity (MW)	33MW
Hub height (m)	80m
Estimated Park Production	84.9 (GWh/year)
Capacity factor	29.4%
Yearly average wind speed at hub height	7.4 m/s
Mean temperature at hub height	12.7°C
Maximum in-flow angle	±2.4°

Financial analysis was also done to evaluate the wind farm project under the fact that financial model for wind farm projects are unique in many aspects. As a matter of the fact the uniqueness is:

- wind farm projects are capital intensive with large amount of upfront investment
- no raw material costs involved
- relatively small portion of operating costs but significant tax related incentive
- Tax related incentive and other cost factors in Jeju Island is different from main land even in Korea

That uniqueness was considered and reflected in financial analysis for decision makers but CAPEX and OPEX data assessed during financial feasibility study couldn't be taken for this thesis due to internal issue in AB wind farm operator, thus real CAPEX and OPEX data was used to estimate LCOE for 20 years for AB wind farm. There should be unascertainable difference because real CAPEX and OPEX are used to estimate and compare LCOE for before and after the wind farm project. However using real CAPEX and OPEX would give more credible LCOE for not only AB wind farm but also future wind power evaluation as reference in Korean market.

Table 6: Practical data for AB wind farm

CAPEX	
CAPEX breakdown for 33MW wind farm	**Total cost**
Wind turbine	$46,200,833
Wind turbine installation	$8,450,000
Transmission	$2,500,000
Other facilities for BoP	$833,333
Electrical layout and construction supervision	$583,333
Spare parts for BoP	$368,333
Special tools for BoP	$77,500
Training	$66,666
Land purchase and compensation expense	$250,000
Total CAPEX	**$59,329,998**
OPEX	
2012 OPEX	$1,425,211
2013 OPEX	$2,422,510
2014 OPEX	$1,223,353
2015 OPEX	$1,822,598
Total Average OPEX	**$1,723,418**
Site Performance	
Estimated Park Production	84.9 (GWh/year)
Capacity factor	29.4%
Estimated wind farm LCOE	
Calculated total LCOE	**0.079$/kWh**

- ✓ Exchange rate ₩1,200 equals $1.
- ✓ Average OPEX was calculated based on annual OPEX from 2012 to 2015. OPEX also include wind turbine O&M costs which is done by the manufacturer. 4 years OPEX was

averaged to calculate representative AB wind farm OPEX. Detail OPEX in each year will be discussed in other sections.

- ✓ Average OPEX also include land lease cost and all of other costs related to wind farm operation and maintenance.
- ✓ Field salaries for the operator are not included in OPEX

CAPEX in Table 6 is one time cost that incurred during wind farm construction and taxes related to the construction is not added. Wind turbine costs proportion take most of total CAPEX of which wind turbine cost is 77% out of total CAPEX. Wind turbine cost varies with countries and has been up and down. As mentioned above estimated OPEX from financial study and real OPEX for certain period of time are not available for the use, so only available OPEX from 2012 to 2015 are used to calculate representative LCOE for AB wind farm. The reason why average OPEX is used is OPEX is different in each year due to variable factors that will be discussed in other sections.

As a result, considering a 33MW wind farm project with a production of 84,989 MWh of electrical energy annually. Assume the following to estimate LCOE:

- CAPEX = $59,329,998 or 1,797$/KW
- Discount rate = 5.5% (recommendable discount rate used in Korean market), life of project = 20 years
- OPEX including wind turbine O&M, land lease, insurance, and all of other costs = $1,723,418

$$\sum_{i=1}^{L} en(i)/(1+r)^i = 1{,}015{,}657\ MWh$$

$$\sum_{i=1}^{L} \frac{rc(i)}{(1+r)^i} + CAPEX = 20{,}595{,}054 + 59{,}329{,}998 = \$79{,}925{,}042$$

LCOE= 0.079 $/kWh

Where i is the year index, L is the life of the wind farm project in years, $en(i)$ is the amount of energy generated in year i, $rc(i)$ is the total recurring cost in year i, r is the discount rate, and CAPEX is the total installed cost.

As a result AB wind farm is profitable in LCOE aspect as electrical price is greater than LCOE and as long as LCOE is less than FIT, which is the minimum price AB wind farm receive, AB wind farm will be profitable during the life time of 20 years. For AB wind farm, pricing of FIT is ₩107 per kWh, which is equal $0.089, for overall life time of wind turbine project FIT is a common pricing model which was introduced to Korea in Oct. 2001. In this model, the price of energy is transparent, fixed, and applies to all producers of renewable electricity. As of March 18th 2010 FIT for wind power is essentially nonexistent in Korea but REC replaced it. AB wind farm is still backed up with FIT, so if unit cost of electric power which is called SMP (System Marginal Price) falls below ₩107 during wind farm project period AB wind farm will receive ₩107 rather than SMP. FIT is minimum cost that AB wind farm can get when SMP get lower than FIT. There will be variation in wind farm operation and maintenance costs and other factors but as a result of feasibility study including financial analysis wind farm turns into profitable project based on data estimated during feasibility study. But this is not known yet if LCOE calculated based on real data also show the same indication. This will be analyzed in other section.

3.4 Analysis of levelized cost of energy for the wind farm

As mentioned above wind farm data is limited but data, used in this thesis, from 2012 to 2015 is actual wind farm data from AB wind farm owner, therefore all of numerical values are correct and represent AB wind farm. CAPEX used in this section is one time charge incurred during wind farm projects, so CAPEX will be common value for each year from 2012 to 2015 whereas OPEX varies with years. Detail cost variation is specified in respective years and wind farm performance data is also included to check the trend and to figure what kind of factor has been impacted on the final result of LCOE.

3.4.1 Levelized cost of energy analysis for 2012

Wind turbine O&M has been done by the manufacturer since 2009 and wind turbine O&M costs are fixed cost. As shown wind turbine O&M cost account for 65.6% of total OPEX followed by insurance that is 12.8% of total OPEX and land lease that is 7.8% and so on. They are annually recurring costs together with other costs stated in Table 7.

Actual wind farm production, yearly average wind speed, capacity factor are less than the estimated data in feasibility study result stated in Table 5. This is basically because the study was based on updated meteorological one year input data of onsite mast with measurement heights up to 60m a.g.l. Even though site specific long-term adjustment reanalysis was done and the extrapolated long term wind speed at hub height conditions is determined by wind flow model, etc. there is still possibility site mean wind speed from one year measurement could be different years to years.

Table 7: CAPEX, OPEX and practical data, and the LCOC estimated for 2012

CAPEX		
CAPEX	CAPEX for wind farm project	$59,329,998
Total CAPEX		**$59,329,998**
OPEX		
Scheduled costs	Labor management	$12,284
	Site facilities, office	$39,253
	Utility bill	$56,444
	Support fund for local society	$49,709
	Land lease	$110,833
	Insurance	$183,333
	Tax and the public utilities charge	$15,280
O&M contract with manufacturer	Wind turbine O&M costs	$936,832
Unscheduled costs	Substation repair	$24,041
Total OPEX		**$1,428,009**
Wind farm Performance and other data		
Actual Wind farm Production		66,831.78 MWh/yr
Capacity factor		23.1%
Wind farm Availability		98.4%
Yearly average wind speed		6.5m/s
Yearly average SMP		$0.20
Discount rate		5.5%
2012 LCOE		
Calculated total LCOE		**0.096$/kWh**

As a result, actual wind farm production for 2012 was 66,831.78 MWh and annual OPEX for 2012 was $1,428,009 which is equivalent to ₩1,713,610,800. CAPEX is not changed as this is one time charge during the wind farm project. To compute LCOE for 2012, the following is enumerated:

- CAPEX = $59,329,998 or 1,797$/KW
- Discount rate = 5.5% (recommendable discount rate used in Korean market)
- OPEX including wind turbine O&M, land lease, insurance, and all of other costs = $1,428,009

$$\sum_{i=1}^{L} en(i)/(1+r)^{i} = 798{,}665\ MWh$$

$$\sum_{i=1}^{L} \frac{rc(i)}{(1+r)^{i}} + CAPEX = 17{,}065{,}254 + 59{,}329{,}998 = \$76{,}395{,}252$$

LCOE = 0.096 $/kWh

Where i is the year index, L is the life of the wind farm project in years**,** $en(i)$ is the amount of energy generated in year i, $rc(i)$ is the total recurring cost in year i, r is the discount rate, and CAPEX is the total installed cost.

Based on the result of LCOE, AB wind farm is profitable in LCOE aspect as average SMP for 2012 is $0.20 which is equivalent to ₩245.
However, LCOE has been increased compared to LCOE result from feasibility study. It is mainly due to lower yearly mean wind speed which eventually caused lower actual AEP while there is not much difference in total OPEX. Thanks to competitive average SMP the wind farm is still profitable but if SMP get lower than FIT of which guaranteed price is $0.089, site development or investment should be reconsidered at this situation in development aspect.

3.4.2 Levelized cost of energy analysis for 2013

As shown in Table 8, 59.1% of total OPEX has been increased compared to 2012 total OPEX. This was mainly because of unscheduled landscaping works that was carried out to make wind farm look better for visitors and the public. It accounts for 24.7% of total OPEX. The percentage of wind turbine O&M costs have been decreased compared to 2012 data but the total amount has been increased.

Table 8: CAPEX, OPEX and practical data, and the LCOC estimated for 2013

CAPEX		
CAPEX	CAPEX for wind farm project	$59,329,998
Total CAPEX		**$59,329,998**
OPEX		
Scheduled costs	Labor management	$13,405
	Site facilities, office	$16,809
	Utility bill	$57,517
	Support fund for local society	$67,875
	Land lease	$110,833
	Insurance	$183,333
	Tax and the public utilities charge	$15,280
O&M contract with manufacturer	Wind turbine O&M costs	$1,288,750
Unscheduled costs	Substation repair	$64,687
	Wind farm landscaping works	$595,833
Total OPEX		**$2,414,322**
Wind farm Performance and other data		
Actual Wind farm Production		73,192.53 MWh/yr
Capacity factor		25.3%
Wind farm Availability		99.2%
Yearly average wind speed		6.7
Yearly average SMP		$0.177
2013 LCOE		
Calculated total LCOE		**0.1008$/kWh**

5% of yearly escalation was added in total wind turbine O&M cost and incentive payment to the manufacturer (contractor) was also made since MAA was higher than the WAA according to AB wind farm. The cost of wind turbine blade upgrade was also added in wind turbine O&M cost. Substation cost also increased because GIS inspection was made in substation. This inspection is carried out every 7 years and the next inspection is planned 2021 according to AB wind farm.

As yearly average wind speed was increased actual AEP for 2013 was also increased compared to 2012. This will eventually impact on 2013 LCOE. Yearly average SMP was decreased to $01.77.

To compute LCOE for 2013, the following is enumerated:

- CAPEX = $59,329,998 or 1,797$/KW
- Discount rate = 5.5% (recommendable discount rate used in Korean market)
- OPEX including wind turbine O&M, land lease, insurance, and all of other costs = $2,414,322

$$\sum_{i=1}^{L} en(i)/(1+r)^{i} = 874{,}679\ MWh$$

$$\sum_{i=1}^{L} \frac{rc(i)}{(1+r)^{i}} + CAPEX = 17{,}065{,}254 + 59{,}329{,}998 = \$88{,}182{,}069$$

LCOE = 0.1008 $/kWh

Where i is the year index, L is the life of the wind farm project in years, $en(i)$ is the amount of energy generated in year i, $rc(i)$ is the total recurring cost in year i, r is the discount rate, and CAPEX is the total installed cost.

Based on the result of LCOE, AB wind farm is profitable in LCOE aspect because average SMP for 2013 is $0.177 which is greater than LCOE. However average SMP has been decreased and it is required to keep an eye on SMP trend since it directly impact wind farm production and profitability.

3.4.3 Levelized cost of energy analysis for 2014

Total OPEX was decreased compared to not only 2013 but also 2012. This was mainly due to wind turbine O&M costs. 5% of yearly escalation was added but incentive payment was not made due to internal debate with the wind turbine O&M contractor. Yearly average SMP and actual AEP were lowest among two years operation. Yearly mean wind speed also dropped to 6.1m/s which mainly impacted on lower actual AEP. Wind turbine O&M accounts for 61% of total OPEX followed by 15% of insurance and 9.6% of land lease, etc. There were not unscheduled activities except a minor substation repair. Total OPEX of 2014 is less than 2012 and 2013 but this does not make 2014 turn into profit year due to lower wind speed, capacity factor, and eventually AEP eventually.

Table 9: CAPEX, OPEX and practical data, and the LCOC estimated for 2014

CAPEX		
CAPEX	CAPEX for wind farm project	$59,329,998
Total CAPEX		$59,329,998
OPEX		
Scheduled costs	Labor management	$11,694
	Site facilities, office	$13,620
	Utility bill	$68,888
	Support fund for local society	$50,728
	Land lease	$117,500
	Insurance	$183,333
	Tax and the public utilities charge	$18,455
O&M contract with manufacturer	Wind turbine O&M costs	$743,668
Unscheduled costs	Substation repair	$5,759
Total OPEX		$1,213,645
Wind farm Performance and other data		
Actual Wind farm Production		63,807.16 MWh/yr
Capacity factor		22.1%
Wind farm Availability		98.6%
Yearly average wind speed		6.1
Yearly average SMP		$0.162
2014 LCOE		
Calculated total LCOE		**0.097$/kWh**

As a result of 2014 performance, estimating accurate wind speed is very important because it directly impact entire wind farm performance and economic result as well.
Availability has been maintained above 96% that is guaranteed performance by the contractor through 2012 to 2014 but it does not mean wind farm actual AEP or capacity factor have been increased thanks to high availability. In other words, conventional availability guarantee is somewhat related to wind turbine production but it is not directly related to maximizing energy production during the life time of the project. It only ensures that turbine is on regardless of production output. In order to make the wind farm more profitable yield based performance guarantee is required as proved in this analysis.

To compute LCOE for 2014, the following is enumerated:

- CAPEX = $59,329,998 or 1,797$/KW
- Discount rate = 5.5% (recommendable discount rate used in Korean market)
- OPEX including wind turbine O&M, land lease, insurance, and all of other costs = $1.213,645

$$\sum_{i=1}^{L} en(i)/(1+r)^i = 762{,}520\ MWh$$

$$\sum_{i=1}^{L} \frac{rc(i)}{(1+r)^i} + CAPEX = 14{,}503{,}522 + 59{,}329{,}998 = \$73{,}833{,}520$$

LCOE = 0.097 $/kWh

Where i is the year index, L is the life of the wind farm project in years, $en(i)$ is the amount of energy generated in year i, $rc(i)$ is the total recurring cost in year i, r is the discount rate, and CAPEX is the total installed cost.
AB wind farm is still profitable in LCOE aspect because average SMP for 2014 is $0.162 that is greater than LCOE. However average SMP has been again decreased through 2013 and 2014. If SMP keeps decreasing each year and get lower than FIT price, wind farm would turn into unprofitable. In this aspect negative SMP trend is also one of cost factor that is directly related to LCOE.

3.4.4 Levelized cost of energy analysis for 2015

Total OPEX was increased. This is basically because of wind turbine O&M costs and substation works. Incentive payment for 2014 which was not paid to wind turbine O&M contractor was added in 2015 wind turbine O&M costs together with 5% of yearly escalation and 2015 incentive payment. Main transformer and main switchgear were inspected in substation so unscheduled costs were also increased. As a result wind turbine O&M costs account for 60% of total OPEX followed by 13.9% of substation repair, 10% of insurance, and 6.4% of land lease.

Total OPEX was increased compared to 2014 data because of 2014 incentive payment which was made to 2015 OPEX and substation repairs. Other costs are almost similar.

Table 10: CAPEX, OPEX and practical data, and the LCOC estimated for 2015

CAPEX		
CAPEX	CAPEX for wind farm project	$59,329,998
OPEX		
Scheduled costs	Labor management	$12,683
	Site facilities, office	$12,517
	Utility bill	$68,888
	Support fund for local society	$50,750
	Land lease	$117,500
	Insurance	$183,333
	Tax and the public utilities charge	$20,883
O&M contract with manufacturer	Wind turbine O&M costs	$1,099,311
Unscheduled costs	Substation repair	$253,304
Total OPEX		**$1,819,169**
Wind farm Performance and other data		
Actual Wind farm Production		57,493.13 MWh/yr
Capacity factor		19.9%
Wind farm Availability		98.5%
Yearly average wind speed		5.89
Yearly average SMP		$0.104
2014 LCOE		
Calculated total LCOE		**0.118$/kWh**

Wind speed was lowest through operation years from 2012 to 2014, thus capacity factor was also decreased below 20%. This was not something the wind farm ever estimated or expected but it happened because unexpected low mean wind speed. Actual AEP also decreased together with SMP. Average SMP is not below FIT but SMP trend have to be monitored and reviewed continuously. If SMP keeps on descending trend the wind farm will not be profitable for the rest of wind farm operation.

To compute LCOE for 2015, the following is enumerated:

- CAPEX = $59,329,998 or 1,797$/KW
- Discount rate = 5.5% (recommendable discount rate used in Korean market)
- OPEX including wind turbine O&M, land lease, insurance, and all of other costs = $1,213,645

$$\sum_{i=1}^{L} en(i)/(1+r)^{i} = 687{,}065\ MWh$$

$$\sum_{i=1}^{L} \frac{rc(i)}{(1+r)^{i}} + CAPEX = 21{,}739{,}765 + 59{,}329{,}998 = \$81{,}069{,}763$$

LCOE = 0.118 $/kWh

Where i is the year index, L is the life of the wind farm project in years, $en(i)$ is the amount of energy generated in year i, $rc(i)$ is the total recurring cost in year i, r is the discount rate, and CAPEX is the total installed cost.

As a result of LCOE calculation, AB wind farm is not profitable in LCOE aspect since LCOE is greater than yearly average SMP that is $0.104. Wind speed and SMP are not something that the wind farm owner can control but they have to check all the trend of wind speed and SMP since they are impacting not only LCOE but also entire wind farm production which directly impact on wind farm profitability. By checking LCOE for 2015 it is assumed that AB wind farm ran a deficit on the wind farm production and it may continue if wind speed and SMP trends are not changed to favorable condition.

3.4.5 Comparison of levelized cost of energy 2012 to 2015

As CAPEX is onetime costs associated with wind farm project development, installation, and commissioning, etc., fixed CAPEX was used as a part of cost factors to calculate each year's LCOE. Therefore CAPEX used in each year is the same factor but OPEX and AEP were variable through 2012 to 2015. Cost elements in OPEX are mostly similar in each year but unscheduled service in substation and incentive payment to wind turbine O&M contractor were main cost factors impacted on total OPEX in each year. OPEX did not vary with wind turbine availability but impacted on LCOE. As data indicated yearly average wind speed impacted on actual AEP and capacity factor, thus it eventually impacted on LCOE in each year though. Wind farm is backed up with FIT but average SMP was not lower than FIT through 2012 to 2015 but LCOE was greater than average SMP in 2015. This theoretically means wind farm was not profitable in 2015 in LCOE aspect while average SMP through 2012 to 2014 was economical since the production could be sold at an effective price that was greater than LCOE.

As SMP price is only comparison criterion of LCOE, each year of SMP data is included in all graphs together with LCOE data to show the result whether the wind farm is profitable or not in LCOE aspect.

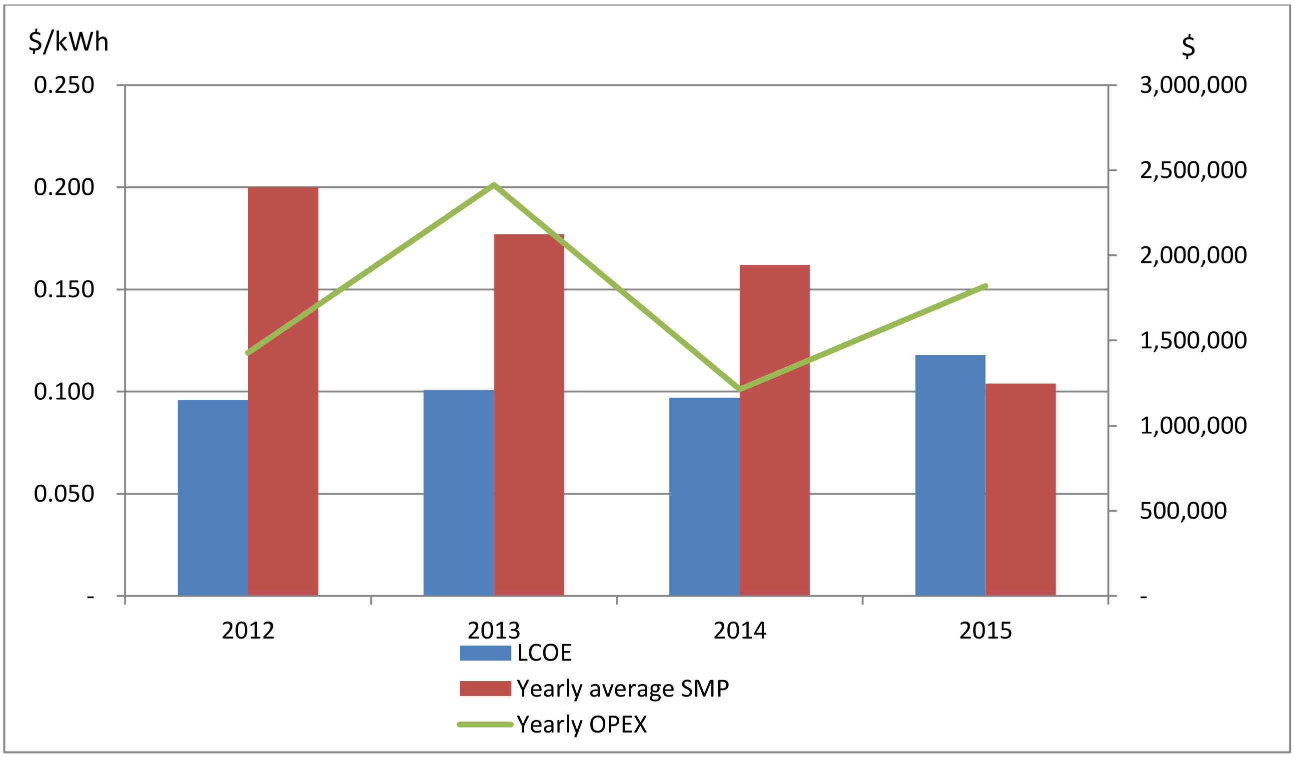

Figure 9: Comparison of LCOE, yearly average SMP and yearly OPEX with years

As shown Figure 9, average SMP was economical in 2012 but decreased continuously till 2015 due to that fact that oil price was also decreased continuously in global.

OPEX variation is not constant but changeable mainly due to unscheduled service. Wind turbine O&M costs is scheduled costs and the payment is made periodically if wind turbine O&M is covered by the manufacturer warranty, but unscheduled service like repair in substation and landscaping works are not predicable and it mostly impact on variable OPEX like year of 2013. Other costs like land lease, insurance, and administrative management are not very changeable but constantly same or similar in each year. LCOE from 2012 to 2014 was economical in LCOE aspect compare to respective average SMP, and their average LCOE is 0.098$/kWh which is also profitable. However LCOE in 2015 was greater than average SMP which means the wind farm is not profitable in LCOE aspect. Increased OPEX somewhat impacted higher LCOE in 2015 but OPEX is not really main factors caused higher LCOE if compared with the result of year of 2013 data. OPEX in 2013 was the highest but LCOE was not highest in 2013. So other factors also need to be checked and reviewed

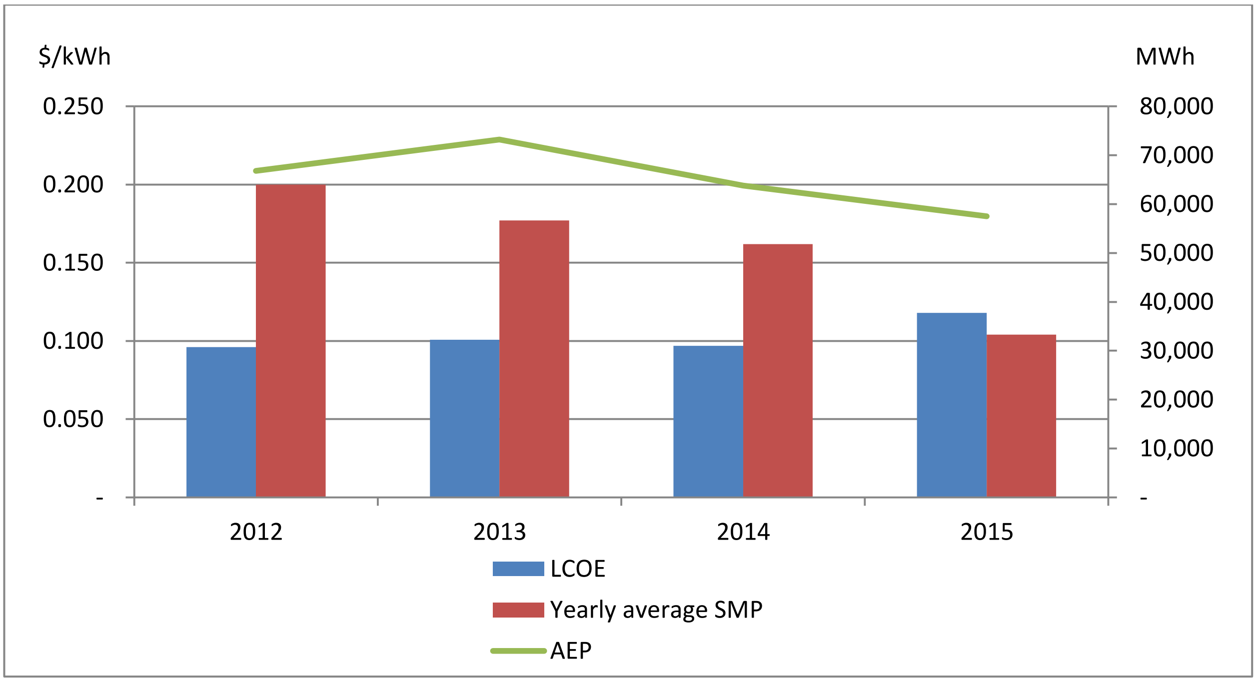

Figure 10: Comparison of LCOE, yearly average SMP and yearly AEP with years

As shown in Figure 10, AEP has been also decreased from 2013 to 2015. AEP in 2013 is the highest but it does not mean LCOE is in 2013 was the lowest. Decreased AEP does impact LCOE but LCOE does not vary with a certain factor solely as seen in Figure 10.

As shown in Figure 11, it is clear that wind speed does impact AEP, so wind measurement during feasibility study is very important to select a potential wind farm.

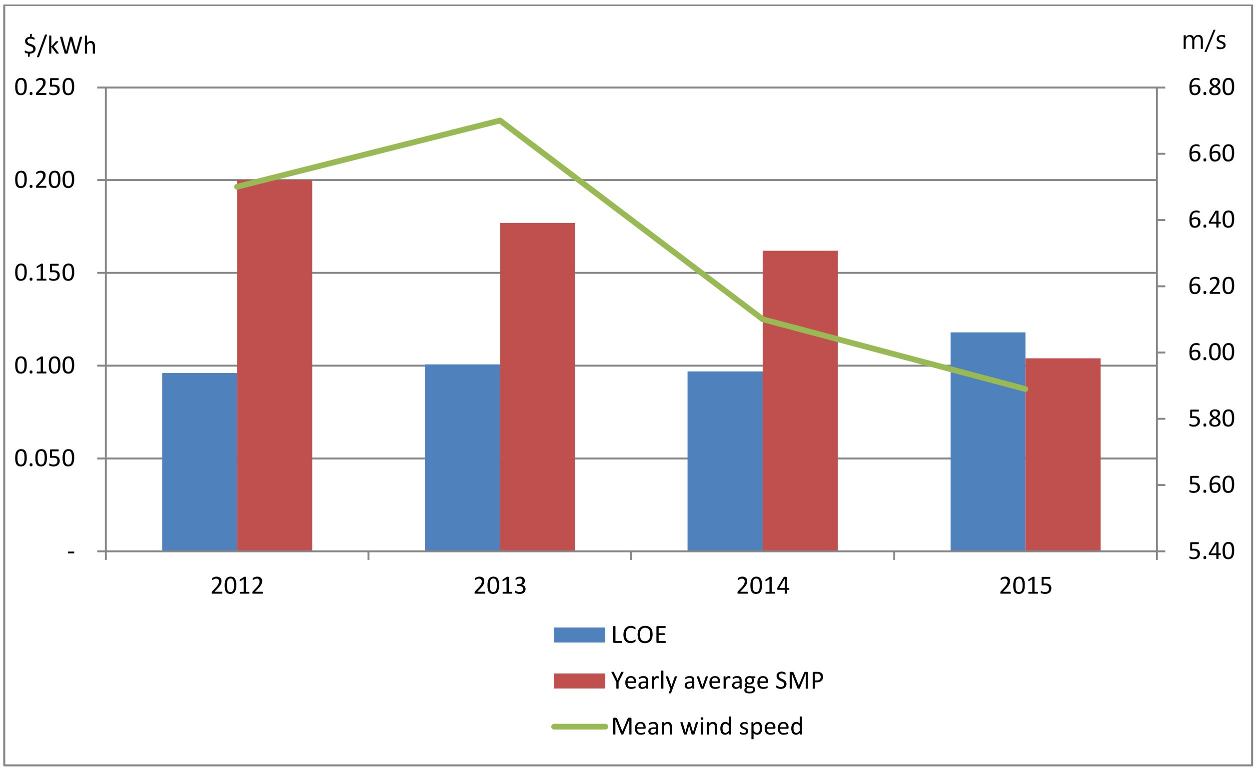

Figure 11: Comparison of LCOE, yearly average SMP and yearly mean wind speed with years

Yearly mean wind speed has been decreased from 2013 to 2015 and that is substantially different from yearly mean wind speed from estimated data from feasibility study.
As mentioned above wind speed does impact AEP, thus LCOE also get impacted. If wind speed and SMP keep on negative trends, the wind farm would never be profitable for coming operation years. As a result unexpectedly decreased SMP and wind speed impacted LCOE in respective year.

4 Discussions

From the result of LCOE and other elements through 2012 to 2015, it is clear that a certain factor does not impact LCOE solely but LCOE vary with combined factors and be associated with factors. Yearly mean wind speed which impacts AEP was substantially different from the estimated wind farm data from feasibility study and it is not predicable for the future operation since the trend is not constant. It is unknown if wind speed would be increased but it is clearly come out that the LCOE highly varies with wind speed. Amount of production yield from the wind farm is an important parameter with a considerable influence on LCOE and the maximum full load hours of a wind farm could be computed from the wind conditions at the wind farm as a function of wind speed. Estimated yearly average wind speed at hub height was 7.4m/s for the wind farm and this wind speed was wind farm representative and was intended to be indicative of wind farm location. However actual average wind speed from 2012 to 2015 was 6.23m/s which may turn into unfavorable wind farm location requiring low wind technology. Wind resource measurement is very important and estimating wind speed may require more conservative approach.

SMP has been decreasing and it is not easy to predict future SMP but SMP will fall continuously till 2024 according to KEEI [22] . As shown in Table 11 SMP trend is not positive for the wind farm and AB wind farm would be also unprofitable since average LCOE is 0.103$/kWh in LCOE aspect.

Table 11: The estimated SMP variation until 2024

Year	SMP
2016	₩90.6 ($0.0755)
2017	₩88.1 ($0.0734)
2018	₩86.9 ($0.0724)
2019	₩87.7 ($0.0730)
2020	₩88.3 ($0.0735)
2021	₩85.3 ($0.0710)
2022	₩79.7 ($0.0664)
2023	₩77.7 ($0.0647)
2024	₩76.7 ($0.06390

SMP in Table 11 was calculated based on a scenario of 7th basic plan for electricity supply and demand from Korea power exchange [22] . This is based on assumption that the 7th plan would be achieved.

AB wind is only profitable when SMP is greater than LCOE (FIT for AB wind farm is $0.089 and average LCOE is $0.103) but as an assumption from the wind farm result LCOE will not be less than $0.096, which is lowest LCOE among year 2012 to 2015 since wind turbines and other facilities get old and require more OPEX costs and average wind speed is still unfavorable. Together with wind speed, SMP is main factor the wind farm should consider about for future operation and maintenance and if two of main factors do not turn into positive the wind farm seriously consider restructuring wind farm operation and maintenance for future operation.

According to KEEI LCOE continuously fall from 140.60₩/kWh, which is equivalent to 0.117$/kWh in 2016 to 136.83₩/kWh, which is equivalent to 0.114$/kWh in 2024 [22] .
LCOE calculated based on a running wind farm is between 0.096$/kWh to 0.118$/kWh which is equivalent 115.2₩/kWh to 141.6₩/kWh through the operation years from 2012 to 2015. This is an actual data, it thus more reliable to predict LCOE for the wind farm. As per predicted LCOE in Figure 12 by KEEI, LCOE for 2016 is 0.117$/kWh and LCOE calculated based on AB wind farm 2015 data is 0.118$/kWh. There is one year gap between LCOE estimated by KEEI for 2016 and LCOE calculation in this thesis for 2015 but the result of LCOE is almost same. Therefore LCOE for coming year for the wind farm would be similar with LCOE KEEI predicted since SMP will fall until 2024 according to KEEI [22] and this may be representative for South Korea.

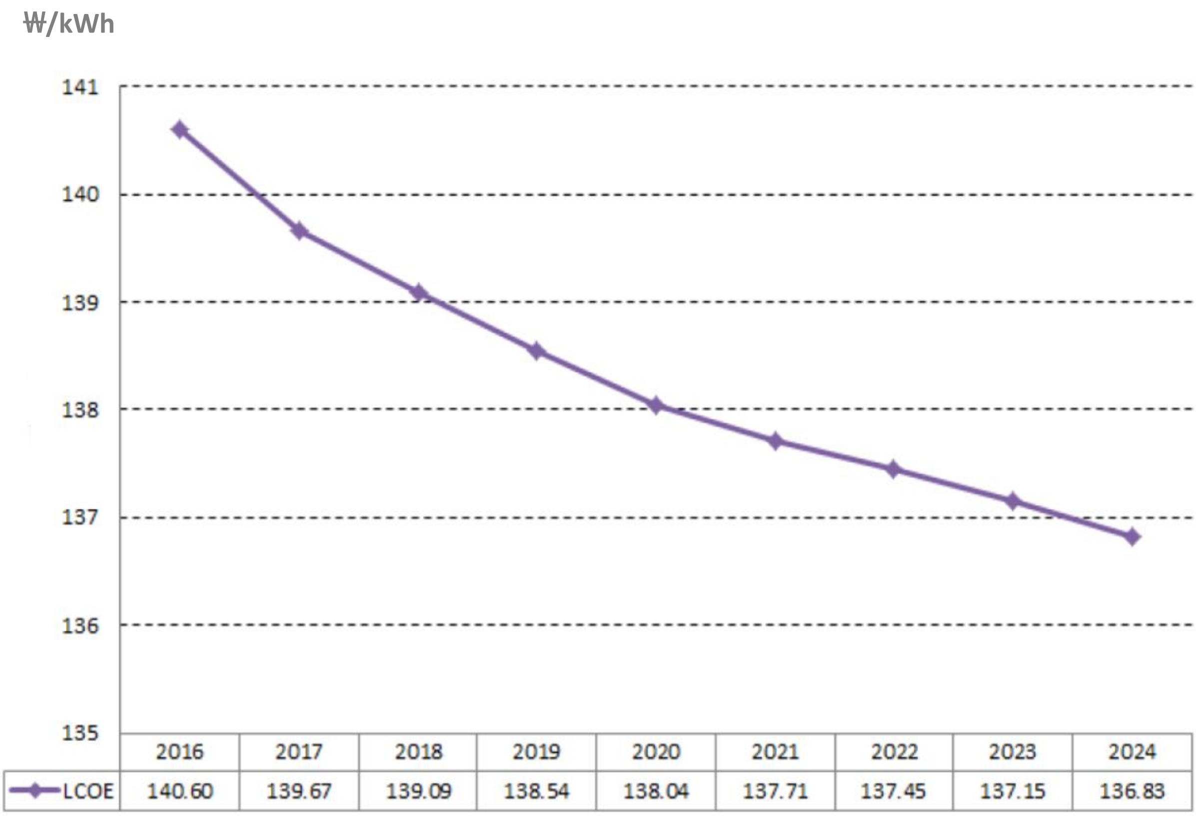

Figure 12: LCOE prediction for onshore wind farm in South Korea [22]

Data in Table 12 was created based on market scenario by BNEF (Bloomberg New Energy Finance) [15] except the data for South Korea which is referred to AB wind farm data. Table 12 originally did not include the data for South Korea but it was added in this thesis with data from AB wind farm as representative data of South Korea.

The range given in Table 12 is an average scenario range and does not represent or reflect actual minimum and maximum values for respective countries except South Korea. They are released to indicate range and trend as reference. 4 years of operation data from AB wind farm is not enough to represent South Korea and estimate future trend but this is worthwhile to compare and analyse the range and trend together.

Table 12: Comparison of LCOEs of AB wind farm of South Korea and other countries presented in ref. [15]

Countries	CAPEX (USDm/MW)	OPEX (USD/MW/yr)	Capacity factor (%)	LCOE (USD/MWh)
S. Korea (AB wind farm)	1.79	52,084 WT O&M(31,251)	23	96-118
India	1.08-1.25	10,694-24,391	15-33	47-113
China	1.36-1.37	17,000-25,138	19-35	49-93
Brazil	1.67	24,000	23-45	55-99
US	1.83	24,000-24,400	20-46	61-136
Australia	2.27-2.45	33,907	30-42	71-99
Europe	1.61-1.94	23,000-28,750	20-36	71-117
UK	1.43-1.52	28,750	28-31	72-74
France	1.43-1.52	20,000-22,500	26-31	75-82
Germany	1.36-1.46	19,000-21,500	24-27	79-82
Sweden	1.59-1.71	19,000-21,500	28-33	79-83
Netherlands	1.44-1.61	20,000-22,500	25-31	79-84
Denmark	1.51-1.61	20,000-22,500	26-30	80-85
Italy	1.46-1.6	20,000-22,000	24-30	87-95
Spain	1.39-1.63	20,000-22,500	26-29	88-91
Poland	1.52-1.73	23,000-24,500	25-30	93-97
Romania	1.61-1.85	22,000-24,500	24-30	100-107
Bulgaria	1.57-1.88	22,000-23,500	24-29	105-106

- ✓ Actual data from AB wind farm was used to represent South Korea
- ✓ CAPEX, OPEX, and capacity factor for South Korea is the average values of AB wind farm's operation year from 2012 to 2015

- ✓ LCOE data for South Korea is the minimum and maximum values of AB wind farm's operation year from 2012 to 2015
- ✓ Three of graph below were created based on data in Table 12.

Figure 13 was created based on data in Table 12. As shown Figure 13, total OPEX for South Korea is $1,718,786 which is equivalent to 52,084$/MW/yr. This consists of 60% of wind turbine O&M cost paid to the contractor (wind turbine manufacturer) as warranty contract payment and 40% of scheduled costs such as land lease, insurance, utility bill, labor management, and support fund for local society and so on of which average scheduled costs are 20,833$/MW/yr. As the O&M warranty contract for AB wind farm includes main component repair, replacement, and 96% of availability guarantee its cost is high and different range from OPEX for other countries.

OPEX range for South Korea is only based on turbine O&M cost which is paid to the contractor. OPEX is still high compared to other countries but it is required to ascertain if wind turbine O&M contract is the same condition or not for better and accurate comparison.

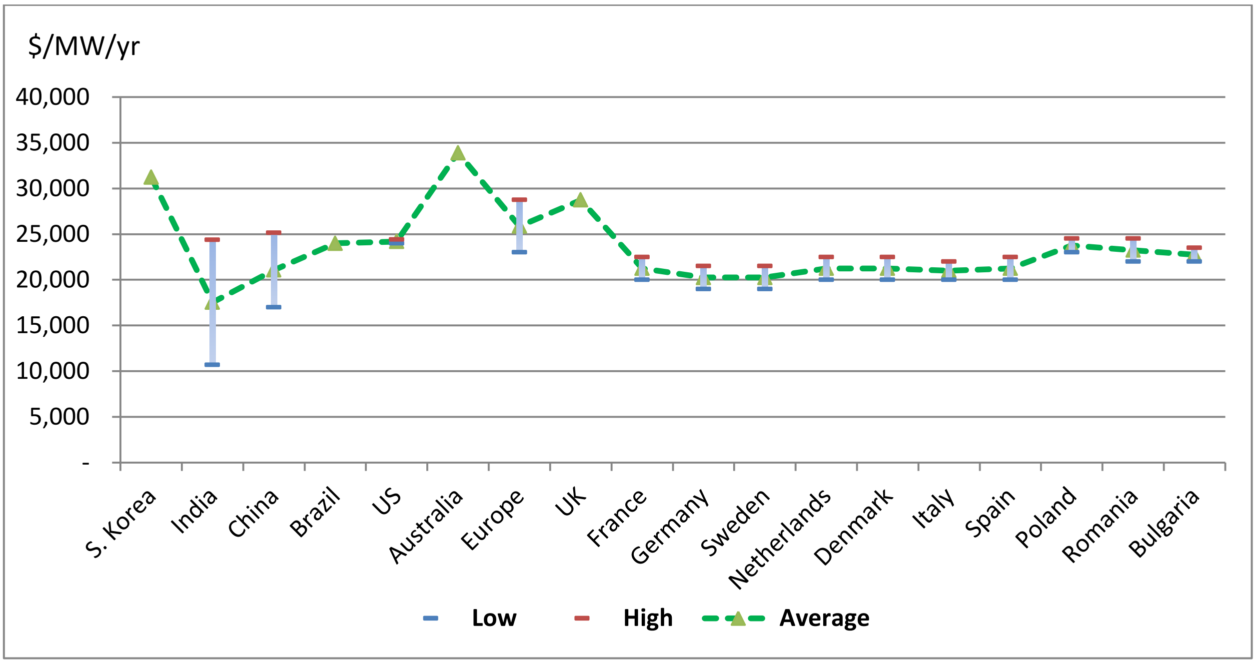

Figure 13: Range of OPEX of onshore wind farm by countries

Capacity factor only represent AB wind farm so the data is very limited to compare with other countries and estimate the trend. However it is good to know that the average wind speed in 2015 was relatively lower than other years nationally. Capacity factor is lower than most of countries but it only represent the wind farm since capacity factor varies with sites and countries.

As shown Figure 14, LCOE is also higher compared to most of other countries but it can represent South Korea as KEEI also predicted similar range of LCOE. As shown in Figure 12, decreasing LCOE trend for South Korea is positive for future wind farms but predicted future LCOE is still high compared to decreasing trend in other countries as shown in Figure 7 and it is not proved whether it can be also applied to the existing wind farms.

Decreasing trend in LCOE can be applied to the future wind farms but it is hard for existing wind farms to apply since most of wind farms are backed up with FIT, and CAPEX, which is fixed, and OPEX, which is annually recurring cost, are already high and difficult to reduce under warranty contract period. Even each year of LCOE for AB wind farm is also not constant but very variable with unscheduled service and unpredicted factors such as low wind speed and decreased SMP, etc. Only way to reduce cost element for the existing wind farms is to reduce OPEX, so next challenge for South Korean market should be discussing and looking into wind farm O&M status.

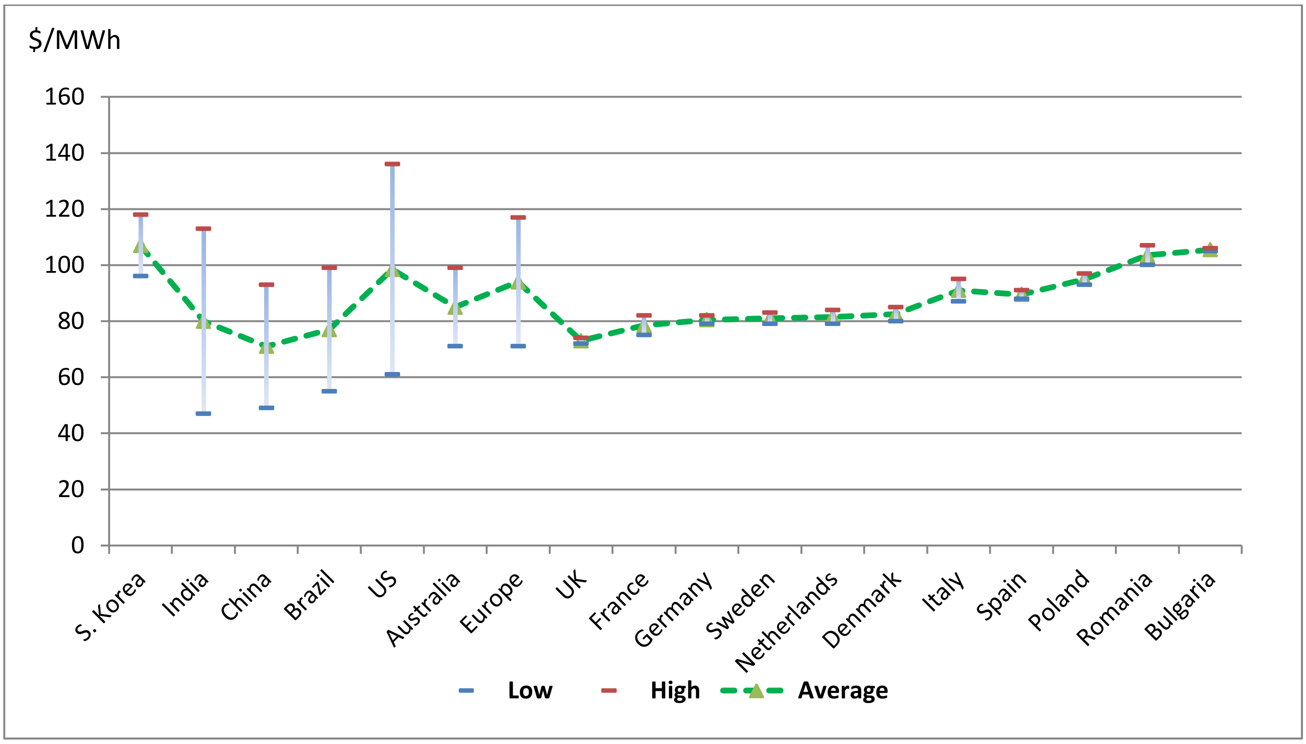

Figure 14: Range of LCOE of onshore wind farm by countries

As shown in Figure 15, CAPEX for AB wind farm which represents South Korea in this thesis is also higher than most of other countries but the range values are not big. The proportion of wind turbine costs is around 77% in total CAPEX which means CAPEX without wind turbine costs are not high compared to other countries since the proportion of wind turbine costs in most of other countries as shown in Figure 4 lower than AB wind farm. However it is required to check more actual data from other wind farms in South Korea to have more reliable data which can represent the trend of South Korea.

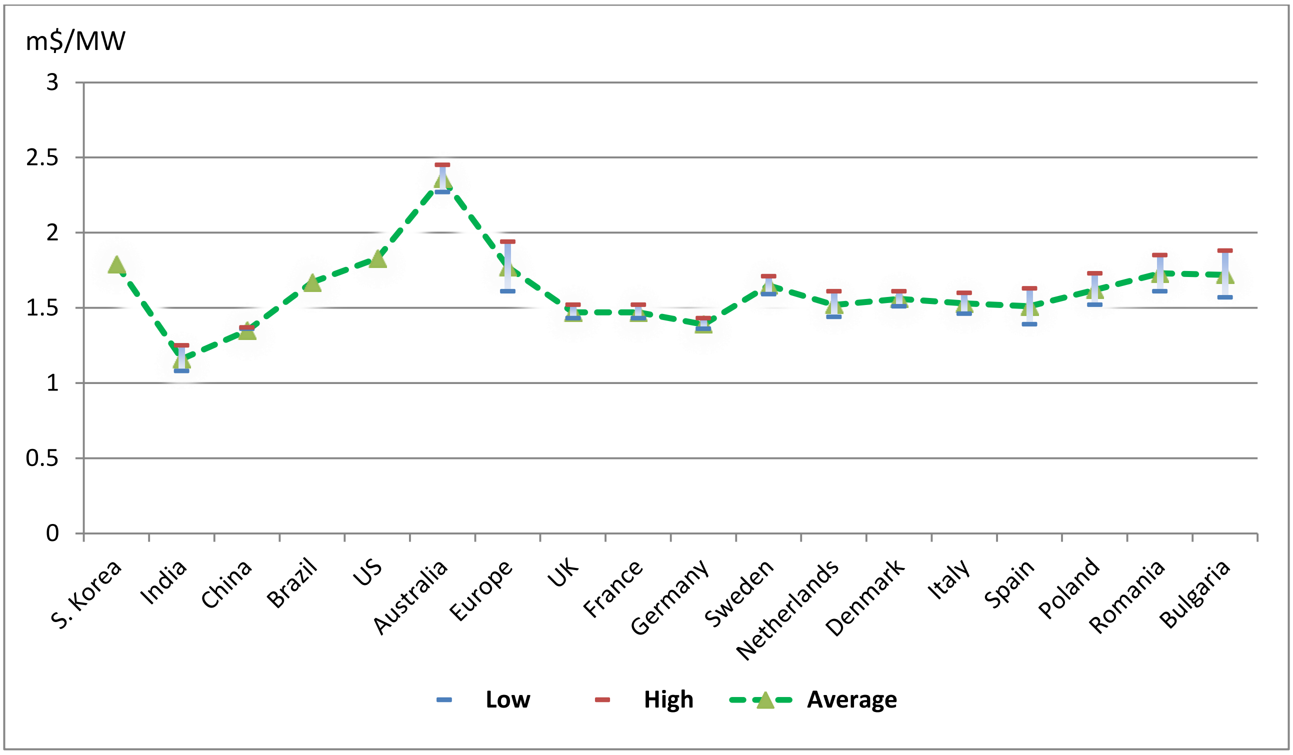

Figure 15: Range of CAPEX of onshore wind farm by countries

Most of countries that are favor in wind power have their own data representing CAPEX, OPEX, and LCOE as reference. This is making good use for all of stakeholders of wind power. Having representative and recommendable CAPEX, OPEX, and LCOE will assist Korea wind power market as well but more researches and studies have to be carried out to reduce uncertainty and predict more reliable data.

4.1 Comparison of estimated and calculated levelized cost of energy for the wind farm

The same amount of CAPEX was used in both LCOE estimation from estimated wind farm data and LCOE calculation from actual wind farm data. Average OPEX of 2012 to 2015 data was used for LCOE estimation since estimated OPEX was not available from the wind farm. Main difference between both estimated and calculated LCOE was AEP, wind speed, and capacity factor. Estimated AEP was much higher than actual AEP since yearly average wind speed was over predicted. If actual LCOE is similar with estimated LCOE the wind farm will be continuously profitable in LCOE aspect regardless of SMP trend since estimated LCOE is $0.079 which is always greater than 0.089$/kWh of FIT.

Table 13: Comparison between estimated data and actual data for AB wind farm

	Estimated data	2012	2013	2014	2015
CAPEX	$59,329,998	$59,329,998	$59,329,998	$59,329,998	$59,329,998
OPEX	$1,723,418	$1,428,009	$2,414,322	$1,213,645	$1,819,169
AEP	84,900MWh	66,831MWh	73,192MWh	63,807MWh	57,493MWh
wind speed	7.4m/s	6.5m/s	6.7m/s	6.1m/s	5.8m/s
CF	29.4%	23.1%	25.3%	22.1%	19.9%
LCOE	0.079$/kWh	0.096$/kWh	0.1008$/kWh	0.097$/kWh	0.118$/kWh

5 Conclusions

The analysis and calculation results led to the following conclusions:

- LCOE for the wind farm in operation was observed to be from 0.096 to 0.118$/kWh which are equal to 115.2 to 141.6₩/kWh
- It is observed unscheduled service such as repair in substation and other wind farm related works mainly impact on OPEX together with incentive payment to the wind turbine O&M contractor.
- LCOE can vary with several key factors but in this study the most influential impact on LCOE is wind speed which eventually impact on AEP and capacity factor.
- CAPEX is $59,329,998 which is equal to 1,797,879$/MW
- OPEX ranged from $1,213,645 to $2,414,322 and the average OPEX is 1,718,786 which is equal to 52,084$/MW/yr. Total OPEX includes 60% of wind turbine O&M cost paid to the contractor as warranty contract payment annually and 40% of scheduled and unscheduled costs for BoP of wind farm operation and maintenance.

This analysis and calculation present a picture of LCOE for a wind farm in operation using real data that represent the wind farm. LCOE calculation in this thesis is only one way to measure the cost of wind power for an operating wind farm. It includes most of costs but discount rate is not real data but assumption from the market value. LCOE is highly sensitive to not only wind speed but also discount rate. So there could be a possibility that LCOE could vary compared to current LCOE calculated in this thesis if different input data is used but it will not be a wide variation in the effect on LCOE.

Over-estimated wind speed during wind resource measurement could lead to wrong investment decision since wind speed impacts on AEP as well as capacity factor which are significant factors for financing assumption. FIT was introduced to support not only wind power technology but also other generating technologies to reduce financial risks and it was expected that FIT would play one of the most important role to support wind farm. It did support wind farm in some of aspects when SMP get lower than FIT but it is not competitive compared to REC and it does not support financial risks in the aspect of LCOE of which the assumption of Korean LCOE based on the result of an operating wind farm is at least minimum 0.103$/kWh which is average LCOE from the running wind farm.

Finally as this thesis clearly demonstrate that changes in wind farm wind speed, AEP, and capacity factor have a significant impact on LCOE that small improvement through wind resource measurement and feasibility study can yield more benefits. It is expected that the result of this thesis give the first realization that would bring more benefit not only for wind farms but also wind industry by reducing uncertainty and examining feasibility for the future wind farm project thoroughly. .

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