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Transition To Sustainability With Natural Gas From Fracking

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TRANSITION TO SUSTAINABILITY WITH NATURAL GAS FROM FRACKING

by

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B.S., University of Science and Technology Beijing, 2012

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This thesis entitled:

Transition To Sustainability With Natural Gas From Fracking

written by Kangqian Wu

has been approved for the Department of Mechanical Engineering

Frank Kreith

Jana Milford

Date_______________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Wu, Kangqian (M.S., Department of Mechanical Engineering)

Transition To Sustainability With Natural Gas From Fracking

Thesis directed by Professor Emeritus Frank Kreith

ABSTRACT

This thesis is an analysis of the energy and money needed to construct a renewable energy system with the excess energy available from natural gas obtained by hydraulic fracturing or “fracking”. Using data from the Energy Information Administration regarding the future availability of natural gas obtained by fracking and the energy required to build a sustainable system consisting of wind power, photo-voltaic energy generation and hydraulic storage, a scenario for the construction of a sustainable system is generated. Greenhouse gas emission reduction by replacing the fossil fuel powered plants with the sustainable system is calculated. Finally, a preliminary financial analysis of the cost of building the renewable system is made. The analysis demonstrates that it is possible to build a sustainable system from the excess natural gas obtained by fracking in less than 30 years. After that time the energy produced from the renewable system is sufficient to replace those parts of the system that have reached their expected life and construct new sustainable generation technology as required by population growth.

This thesis is dedicated to my beloved girlfriend Selina Hu.

ACKNOWLEDGMENTS

I would like to acknowledge Professors Frank Kreith, R.E.West and Jana B. Milford of the University of Colorado Boulder and Dr. Victor Diakov of National Renewable Energy Laboratory for valuable input and the CU Retired Faculty Association for providing some funding for this work. I also need to thank my parents and my girlfriend for their support and love. Finally, I would also like to thank Mrs. Marion Kreith for her wonderful coffee when we had meetings in her house.

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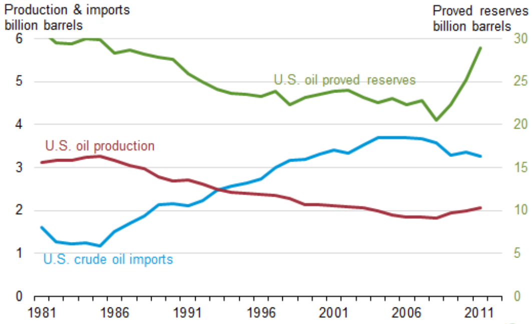
1 INTRODUCTION

The impacts of anthropogenically produced greenhouse gas emissions on the earth's climate are of growing concern. CO_2 emission from fossil fuel combustion is a key factor of climate change. According to International Energy Agency (IEA), fossil fuel power industry accounted for 40% of global CO_2 emissions in 2010 [1]. In addition to global warming, air pollution from burning of fossil fuels is a major problem in developing countries, such as China and India.

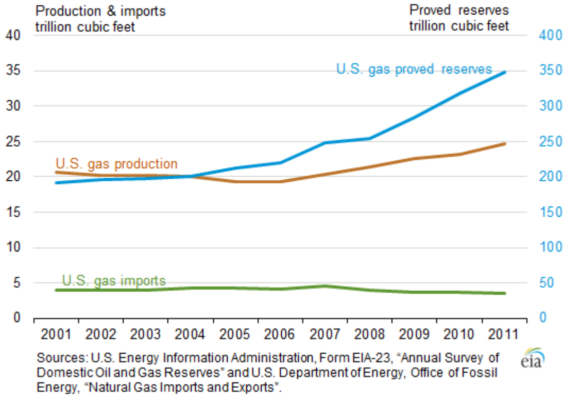
1.1 FRACKING

Figures 1 and 2 show respectively the U.S. crude oil and natural gas reserves, production and imports [2]. After 2008 the wide application of horizontal drilling and hydraulic fracturing (fracking) increased the proven and economically accessible oil and natural gas reserves in shale formation. According to Figure 2, between 2008 and 2011, natural gas production increased from 20 trillion cubic feet to 25 trillion cubic feet, mostly as a result of horizontal drilling in tight formations that were heretofore inaccessible.



Sources: U.S. Energy Information Administration, Form EIA-23, "Annual Survey of Domestic Oil and Gas Reserves", and Form EIA-814, "Monthly Imports Report".

Figure 1. U.S. Crude Oil Reserves, Production, and Imports, 1998-2011



Sources: U.S. Energy Information Administration, Form EIA-23, "Annual Survey of Domestic Oil and Gas Reserves" and U.S. Department of Energy, Office of Fossil Energy, "Natural Gas Imports and Exports".

Figure 2. U.S. Natural Gas Reserves, Production, and Imports, 2001-2011

According to the U.S. Environmental Protection Agency (EPA), hydraulic fracturing is a process to stimulate a natural gas well to maximize the extraction. Induced hydraulic fracturing or "fracking" is a technique in which typically water is mixed with sand and chemicals, and the mixture is injected at high pressure into a wellbore to create small fractures (typically less than 1mm), along which fluids such as gas or petroleum may migrate from tight formation such as shale to the well. The technique combined with horizontal drilling is commonly used to extract natural gas from tight formation as shown in Figure 3.

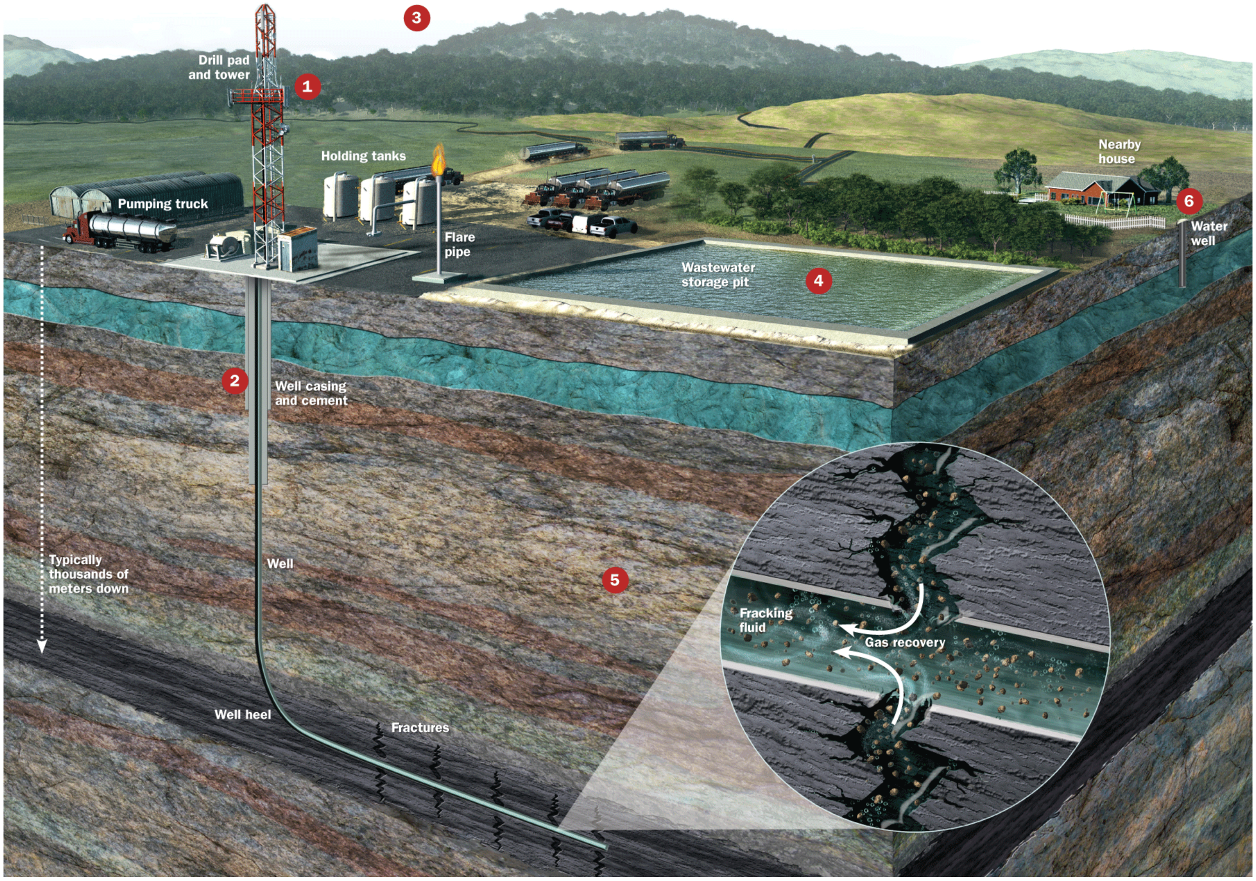


Figure 3. Schematic Diagram of Fracking

Fracked natural gas is an unexpected new energy source, but it is still fossil fuel and should be used to build sustainable energy systems to replace traditional fossil fired power plants before it too runs out.

1.2 WIND,WATER STORAGE AND SOLAR PV SYSTEM (WWS)

Wind and solar photovoltaics (PV) are the fastest growing renewable technologies. The cost of the electric energy from these sources is close to that from fossil fuel plants. But wind and solar vary with time and location. This is perceived as a major problem in employing these abundant resources. On average, wind blows more at night and solar is only available during the day. Thus, a combined wind and PV system with storage could provide a relatively stable electricity source.

According to Short and Diakov [3], 83% of the total US electricity demand can be provided by a combination of wind and solar PV with about 40 GigaWatts of hydro storage. The analysis in this thesis shows that if the available natural gas energy from fracking is used to build a WWS system, it will take 30 years to provide 83% of US electricity demand with the optimal ratio of wind to PV capacity. The remaining 17% of current demand would have to be met by energy conservation or dispatchable energy generators such as natural gas turbines or geothermal energy. This replacement of fossil fuel power plants by renewable sources will have a favorable impact on the environment.

This thesis analyzes how fracked natural gas can build a WWS system. The major assumption is that natural gas can replace all forms of energy that are used in manufacturing and building the wind and PV plants.

2 ENERGY ANALYSIS

This chapter describes the energy analysis used to build the WWS system.

2.1 EROI METHOD

In large scale energy analysis, the Energy Return On Energy Investment (EROI) method is widely used. EROI is defined as the net electric energy output during the lifetime of the system (E_{out}) divided by the energy required to build, operate, and decommission the system (i.e. energy investment E_{inv}) [4]. For a power plant, E_{out} is equal to the product of the plant capacity (Ca), the capacity factor (CF) (capacity factor is the ratio of the actual output of a power plant over a period of time to its potential output if it were to operate at full nameplate capacity) and the system lifetime (L). Thus, the EROI for wind and PV are:

$$\mathrm{EROI_{wind}} = \frac{\mathrm{Ca_{wind}(t) \times CF_{wind} \times L_{wind}}}{\mathrm{E_{inv,wind}(t)}} \qquad (1)$$

$$\mathrm{EROI_{PV}} = \frac{\mathrm{Ca_{PV}(t) \times CF_{PV} \times L_{PV}}}{\mathrm{E_{inv,PV}(t)}} \qquad (2)$$

where Ca(t) is the capacity built in year t and $E_{inv}(t)$ is the energy invested to build sustainable systems in year t. Values of EROI, Ca, and L for wind and PV are available in the literature [5-17].

Short and Diakov have developed a linear model that meets all the load demands while minimizing the energy from dispatchable and curtailed energy [3]. According to that model, the optimal ratio of wind and PV generation to meet the electricity demand for the year of the analysis is:

$$\frac{\mathrm{Ca_{wind}(t)}}{\mathrm{Ca_{PV}(t)}} = \frac{100}{71} \tag{3}$$

Assuming that all the available fracked natural gas in year t, $E_{ava}(t)$,is used for the construction of wind and PV plants,

$$\mathrm{E_{inv,wind}(t) + E_{inv,PV}(t) = E_{used}(t)} \tag{4}$$

until 83% of the electricity demand is met.

Thus the total installed capacity of wind [$\mathrm{Ca_{wind_{tot}}(t)}$] and PV [$\mathrm{Ca_{PV_{tot}}(t)}$] plants in year t is:

$$\mathrm{Ca_{wind_{tot}}(t) = Ca_{wind}(t) + Ca_{wind_{tot}}(t-1) - Ca_{wind}(t-L)} \tag{5}$$

$$\mathrm{Ca_{PV_{tot}}(t) = Ca_{PV}(t) + Ca_{PV_{tot}}(t-1) - Ca_{PV}(t-L)} \tag{6}$$

where t<L and $\mathrm{Ca(t-L) = 0}$. Using equations (1)-(6), wind and PV capacity built in year t can be calculated, assuming that the wind to PV ratio from reference [3] applies for the entire period.

The electricity generated in year (t+1), $E_{ele}(t+1)$, from all the plants built in year t is:

$$\mathrm{E_{ele}(t+1) = Ca_{wind_{tot}}(t) \times CF_{wind} + Ca_{PV_{tot}}(t) \times CF_{PV}} \tag{7}$$

After 83% of the electricity demand is met, energy is only needed to meet the yearly increase in electricity demand and the replacement of the wind and PV systems that have reached their useful life. Hence, the newly increased demand in year t is:

$$\mathrm{A(t) = 83\% \times E_{demand}(t+1) - E_{ele}(t)} \tag{8}$$

where $\mathrm{E_{demand}}$ is obtained from the EIA [2].

As some renewable plants reach their lifetime (t>L), the electricity that was generated by these plants in year t, B (t), is:

$$B(t) = Ca_{wind}(t - L_{wind}) \times CF_{wind} + Ca_{PV}(t - L_{PV}) \times CF_{PV} (9)$$

and the capacity that needs to be built in year t is:

$$Ca_{wind}(t) \times CF_{wind} + Ca_{PV}(t) \times CF_{PV} = A(t) + B(t) \qquad (10)$$

Using (3) and (10), one can calculate the wind and PV capacity built in year t after 83% of the U.S. electricity demand is matched.

To calculate the electricity generation, the performance values shown in Table 1 were used [5].

Table 1. Assumptions for Wind and PV

Item	Unit	Value
Capacity factor of wind	-	35%
Capacity factor of PV	-	25%
Life time of wind	Year	25
Life time of PV	Year	25

The EROI method was used in this thesis to calculate the energy output during the plants' lifetime. There have been several studies of EROI for sustainable energy systems and Tables 2 and 3 show EROIs of wind and PV from the literature.

Table 2. EROI for Wind Plants (Refs. 6-11)

Reference	Year	Original EROI	Standardized EROI
[6]	1998	38.86	32.38
[7]	2000	51.30	56.11
[8]	2007	34.36	65.93
[9]	2008	19.20	44.21
[10]	2012	30.59	39.24
[11]	2012	27.01	39.38

Table 3. EROI for PV Plants (Refs. 12-17)

Reference	Year	Original EROI	Standardized EROI
[12]	1995	2.17	3.62
[13]	2000	2.75	2.29
[14]	2007	2.67	3.10
[15]	2008	5.48	4.42
[16]	2011	4.58	3.76
[17]	2012	5.90	4.92

The results of an EROI analysis depend on the assumptions used by the investigator. Different assumptions, such as lifetime of the system, will lead to a difference of the life time energy output of a sustainable energy system. To compare those different EROIs, it is therefore necessary to standardize the original values to similar operating parameters and boundary conditions [18] as shown in Table 1 [For the Calculations See Appendix A]. The Standardized EROI column in the above tables shows the results after standardarization. For the analysis in this thesis, the average value of EROIs reported for the years (2011-2012) will used; hence $EROI_{wind} = 39.31$ and $EROI_{PV} = 4.34$.

2.2 FRACKED NATURAL GAS AVAILABLE FOR CONSTRUCTION

According to EIA's Energy Outlook 2013 [4], the annual growth rate of fracked natural gas production is expected to be 2.64% for the next 30 years. . Since all the natural gas currently produced is under contract, only the difference between future production and current production can be used for the construction of a sustainable energy system. Assuming that year 2013 is the base year, the natural gas energy available for the construction in year t (Figure 4) is the difference in production of natural gas from fracking in year t and that in year 2013 [2].

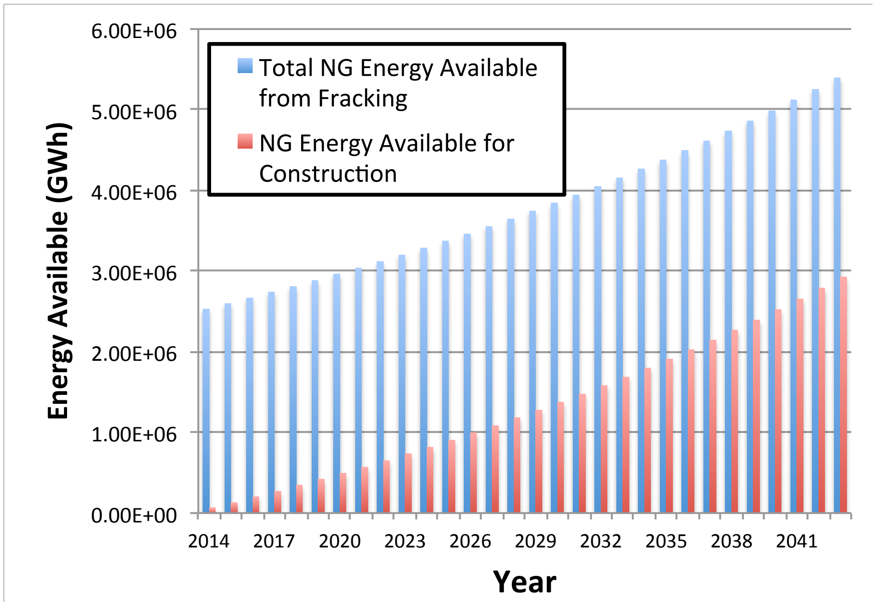


Figure 4. Comparison of Total Natural Gas Energy from Fracking and Natural Gas Energy Available for Construction

2.3 CAPACITY BUILT EACH YEAR

This section presents the method used to calculate the yearly capacity built.

2.3.1 Using All the Available Energy for Construction

The above approach is used to examine how to match the next 30 years' loads in U.S. with wind and PV plants. The results are shown in Figures 5 and 6.

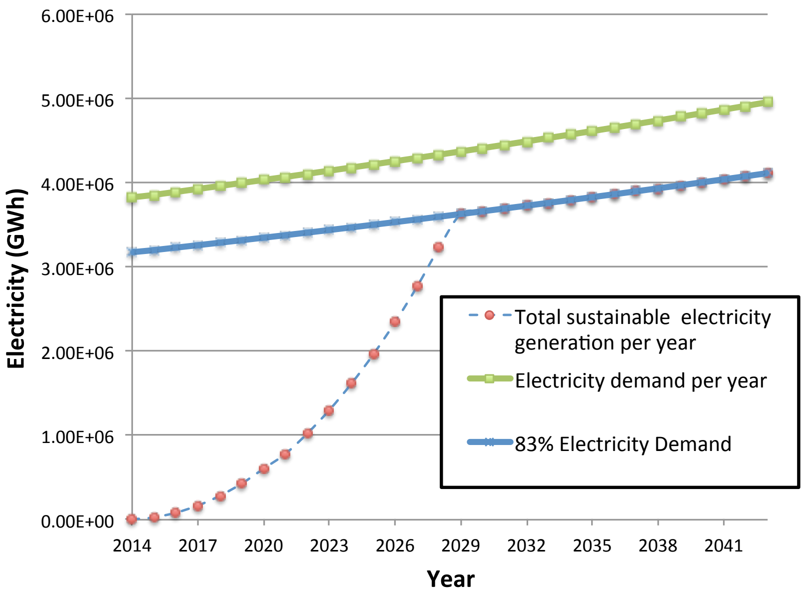


Figure 5. Sustainable Electricity Generation and Electricity Demand for Year 2014 to 2043

It can be seen that the total electricity demand will be met 15 years from now with a total of 785 GW wind plants and 558 GW PV plants built at the end of that year.

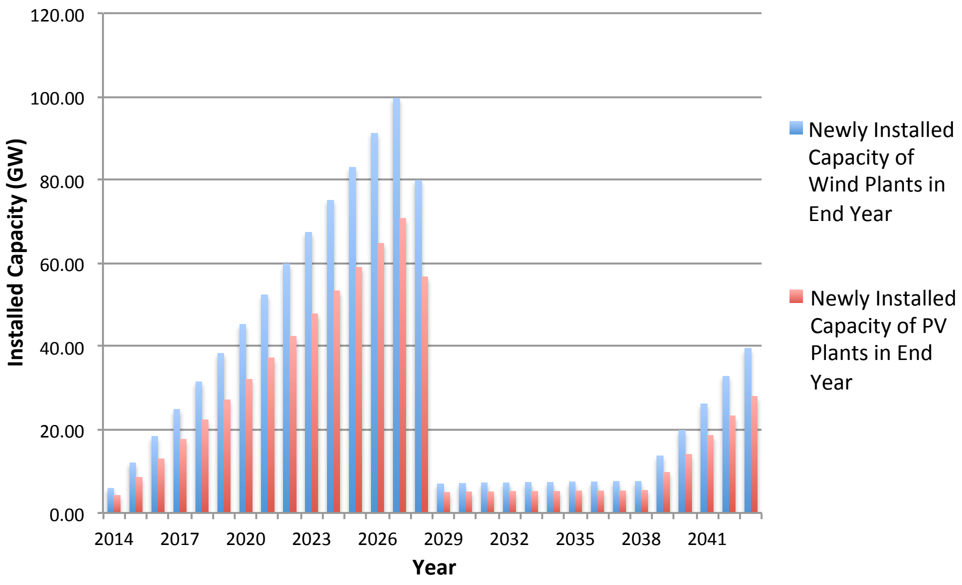


Figure 6. Newly Installed Capacity of Wind and PV Plants Per Year

Figure 6 shows that the construction need in year 2029 drops dramatically because the total capacity built in 2028 meets 83% of the electricity demand and in 2029 no plants are retired because their lifetime of 25 years has not been reached. Newly built capacity is just enough to meet the yearly increased electricity demand, which is relatively small. Thus, a big drop of capacity in the building industry appears. This drop could create problems to economy because the supply exceeds the demand by a large amount. This situation is happening in China now. The PV panels' demand for Chinese manufacturer several years ago was driven by the huge markets in Europe and North America. The PV construction capacity by the Chinese companies increased their PV building rate significantly as Figure 6 shows. Suddenly, when European and American governments placed high taxes on these Chinese PV panels, demand decreased precipitously as a result and many Companies in China went bankrupt, factories were closed and employees in the PV industry lost their jobs.

2.3.2 Modified Construction Plan

To avoid this catastrophic drop, one can slow down the construction rate and decrease $E_{used}(t)$, the natural gas used for construction of renewable plants. Figures 7 and 8, respectively, show the results of the modified construction plan. According to this plan, from year 2014 to 2018, all the available fracking natural gas is used, while during 2019 and 2043, only 390 TWh of fracked natural gas energy is used every year for WWS construction, and in year 2043, the electricity demand is met.

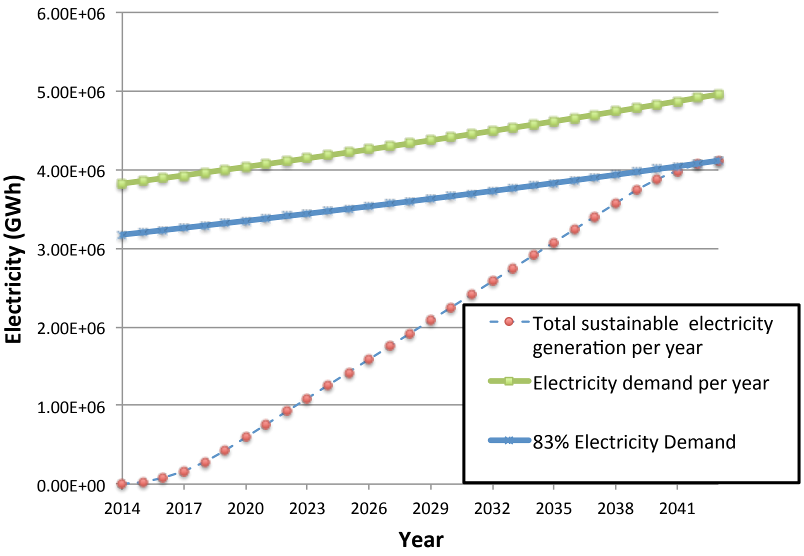


Figure 7. Modified Sustainable Electricity Generation and Electricity Demand for Year 2014 to 2043

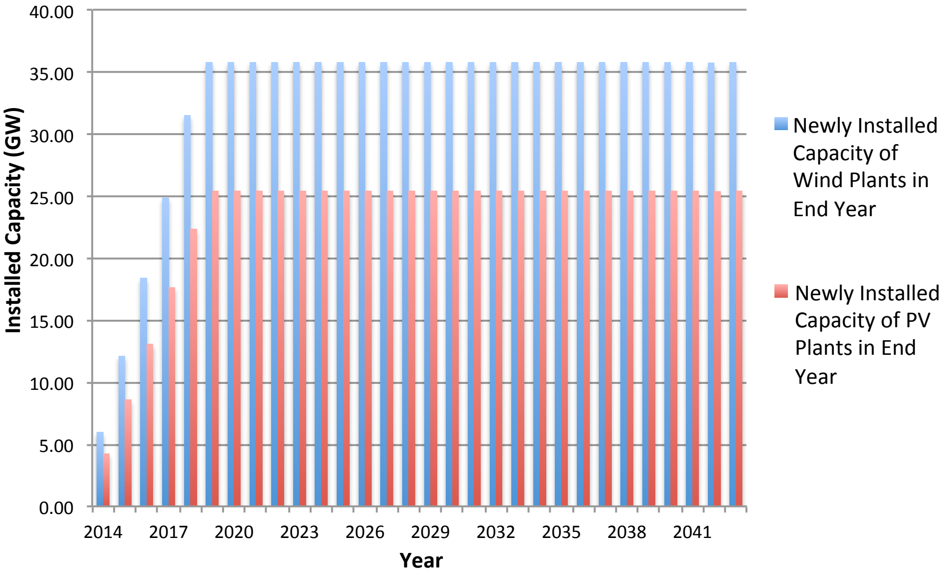


Figure 8. Modified Newly Installed Capacity of Wind and PV Plants Per Year

2.4 PRIMARY ENERGY SAVED

Fracked natural gas is used to build a renewable system to replace the fossil powered plants. The amount of primary energy reduced by replacing traditional fossil plants is examined in this section.

2.4.1 Electricity Generation Structure

According to EIA [2] in 2011 42% of electricity generation came from coal plants, 24% from natural gas plants, 19% from nuclear plants, 13% from renewable energy plants and 2% from others. To replace the existing power plants with a combined Wind and Solar PV System (WWS), the following assumptions are made:

1) The percentage of the total U.S. generation for the sources listed above will not change for the next 30 years if WWS were not built.
2) WWS will replace all the coal and natural gas plants and generate 83% of total electricity demand [3]. Another assumption made is that the increasing demand will be met by increasing the capacity of wind and PV at the same ratio ($\frac{\mathrm{Ca_{wind}}}{\mathrm{Ca_{PV}}} = \frac{100}{71}$) [19]. The remaining 17% of supply could come from natural gas turbines, small hydro, and geothermal.
3) The average power generation efficiency of coal and natural gas plants will not change over the next 30 years.

2.4.2 Primary Energy Reduction

The heat rate, which is the amount of primary energy in Btu used by an electrical power plant to generate one kilowatthour (kWh) of electricity, is usually used as a measure of power plant efficiency. According to EIA, the heat rate for coal plants in U.S. is 10471 Btu/kWh (3.07 kWh(primary energy)/kWh(electric energy)), and 8096 Btu/kWh(2.37 kWh(primary energy)/kWh(electric)) for natural gas plants. The reduction in primary energy use in year t by replacing the coal plants E_{red_coal} (t) is:

$$E_{red\_coal}(t) = E_{ele}(t) * p_{coal} * R_{coal} \quad (11)$$

and that by replacing the NG plants E_{red_NG} (t) is:

$$E_{red\_NG}(t) = E_{ele}(t) * p_{NG} * R_{NG} \qquad (12)$$

where,

E_{ele} (t) is the electricity generated by WWS in year t.

p is the percentage of power generation in U.S. 42% for coal and 24% for natural gas.

R is the heat rate for a given type of power plant, kWh(primary energy)/kWh(electricity).

The total primary energy reduction by WWS over 30 years is thus:

$$E_{red\_}tot = \sum_{1}^{t=30}(E_{red_{coal}}(t) + E_{red_{NG}}(t)) \quad (13)$$

and the total primary energy used to build WWS is

$$E_{used\_}tot = \sum_{1}^{t=30}(E_{used}(t)) \qquad (14)$$

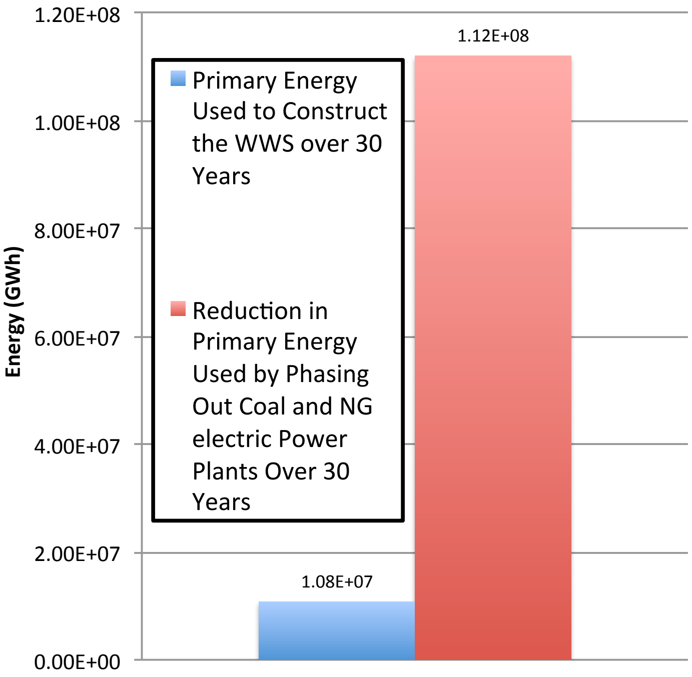


Figure 9. Comparison of Primary Energy Used to Construct the WWS and Reduction in Primary Energy Used by Phasing Out Coal and NG Electric Power Plants Over 30 Years

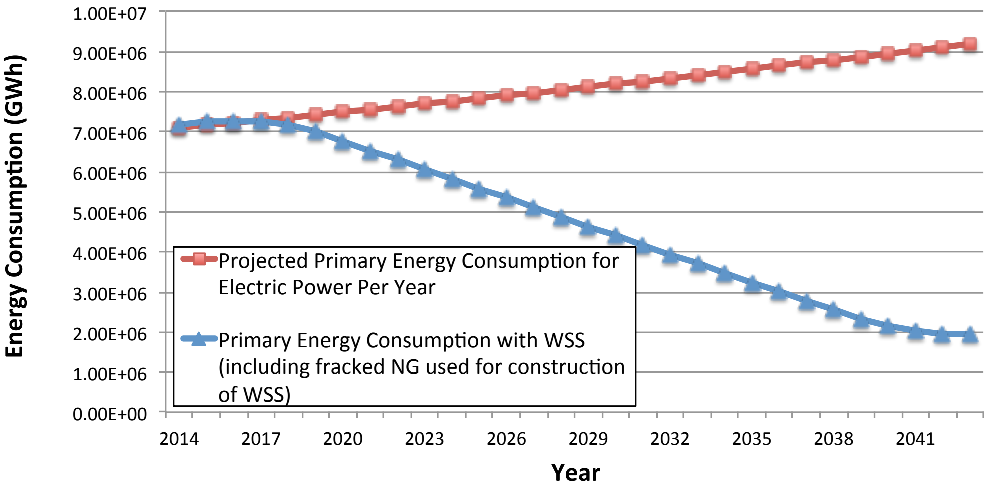


Figure 10. Comparison of Projected Primary Energy Consumption for Electric Power Per Year and Primary Energy Consumption with WWS (including fracked NG used for construction of WWS)

Figure 9 compares the primary energy of the fracked natural gas for construction of the WWS system and the reduction in primary energy by phasing out fossil power plants over 30 years. The difference between them is the net reduction. The results show that building the WWS will reduce fossil fuel consumption significantly. This result ignores the energy input to build fossil powered plants to meet the increases of electricity demand and replace the out dated plants, if no WWS were to be built. Also the efficiency of producing and distributing coal and natural gas is neglected.

Figure 10 shows the projected yearly primary energy consumption for electric power if there is no WWS built and the one when a WWS system is built. The area between the two curves represents the net reduction in primary energy used.

3 ENVIRONMENTAL IMPACTS

Although there are anecdotal claims of water pollutions due to fracking, the Interstate Oil and Gas Compact Commission (IOGCC) and Environmental Protection Agency (EPA) have never found a case of underground water contamination due to fracking that could be proved. In Colorado the legal requirement by Colorado Oil and Gas Conservation Commission is

> "Under Rule 324A, Colorado strictly prohibits pollution of water from oil and natural gas drilling. The Colorado Oil and Gas Conservation Commission (COGCC) and the Colorado Department of Public Health and Environment (CDPHE) regulate the oil and gas industry's operations from start to finish to ensure surface and subsurface water is protected."

Lisa Jackson, the former EPA administrator, also stated that "I'm not aware of any proven case where the fracking process itself has affected water..." (http://lonelyconservative.com)

Since no verifiable information about water pollution could be found in pure reviewed literature, greenhouse gas (GHG) emission was the only environment consequence of fracking that was considered in this thesis. This chapter presents an estimate of the reduction in GHG emission by phasing out fossil fuel powered plants with a WWS renewable system.

3.1 GREENHOUSE GAS EMISSIONS

One of the most important reasons why some people oppose fracking is that leakage of methane (CH_4), which is a significant constituent of any type natural gas operation, may lead to global warming since methane has high Global Warming

Potential (GWP). GWP is a measure of how much a greenhouse gas heats the atmosphere and contributes to global warming by trapping solar radiation. However, a large multi disciplinary investigation by experts from Stanford University, National Renewable Energy Laboratory, University of Michigan, MIT, University of Colorado, Harvard University and Lawrence Berkeley National Laboratory [20], claims that "hydraulic fracturing for NG is unlikely to be a dominant contributor to total emissions". The authors of reference [20] also found that system-wide leakage of methane is not large enough to negate climate benefits of fossil-to- NG substitution.

This thesis estimates the amount of CO_2 emission from combustion and the methane emission due to leakage with and without the WWS. Combustion by coal power plants as well as natural gas plants produces large amounts CO_2 and the use of natural gas also emits methane by leakage. When these fossil-fueled power plants are replaced by WWS, GHG emissions will be reduced. However, when WWS plants are built with natural gas from fracking, some appreciable amount of GHG is leaked into the atmosphere.

3.2 CO_2 EMISSIONS REDUCTION

According to International Energy Agency [21], the average CO_2 emission per kWh in U.S. from coal plants electricity generation is 334.4 g/kWht and that from natural gas plants is 181.1 g/kWht. Hence, the total reduction in CO_2 emission in year t is:

$$\mathrm{CO_{2}}_{\mathrm{red}}(\mathrm{t}) = \mathrm{E}_{\mathrm{red\_coal}}(\mathrm{t}) * \mathrm{e}_{\mathrm{coal}} + \mathrm{E}_{\mathrm{red\_NG}}(\mathrm{t}) * \mathrm{e}_{\mathrm{NG}} \quad (15)$$

where,

e_{coal} is the emission rate from combustion of coal in grams CO_2 per kWh of primary energy.

e_{NG} is the emission rate from combustion of natural gas in grams CO_2 per kWh of primary energy.

To estimate the CO_2 emitted by combustion of fracked natural gas, assume that to build the wind and PV plants, all the energy in natural gas is turned into electricity energy. Since energy from NG is calculated using the EROI method, the natural gas energy E_{used} is the primary energy, E_{used} divided by the heat rate is the electricity energy. Hence, CO_2 emitted by combustion of fracked natural gas in year t is:

$$CO_{2_{emit}}(t) = E_{used}(t) * e_{NG} \quad (16)$$

where $E_{used}(t)$ is the energy from fracked natural gas used to build WWS in year t.

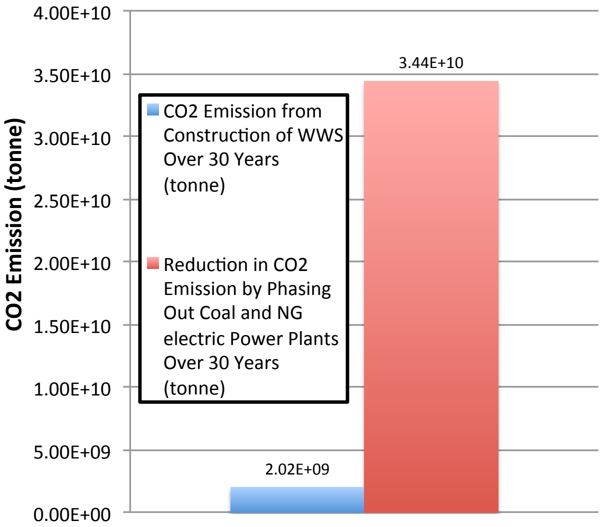


Figure 11. Comparison of CO_2 Emission from Construction of WWS and Reduction in CO_2 Emission by Phasing Out Coal and NG Electric Power Plants Over 30 Years

3.3 METHANE LEAKAGE REDUCTION

Methane leakage occurs not only in the field during production, but also in processing, transmission, storage, and distribution. According to US Environmental Protection Agency (EPA), the total methane emission from all natural gas systems in 2011 was 6893 Gg, including hydraulic fracturing [22]. In 2011, the total production of natural gas in U.S. was 23.5 trillion cubic feet. So the leakage can be calculated, which is 0.0145 grams of methane per gram of natural gas usage (i.e. ~1g CH_4/kWh primary energy). Even though EPA's estimates have changed from year-to-year due to changes in methods and assumptions, a constant rate of 1.45% was assumed in this thesis. Thus, so the reduction in methane leakage is:

$$\mathrm{CH}_{4_{\mathrm{red}}}(\mathrm{t}) = \mathrm{E}_{\mathrm{red\_NG}}(\mathrm{t}) * \mathrm{me} \qquad (17)$$

where,

me is the methane leakage in grams per kWh of primary energy.

The methane leakage from the use of fracked natural gas to build the WWS plants is:

$$\mathrm{CH}_{4_{\mathrm{emit}}}(\mathrm{t}) = \mathrm{E}_{\mathrm{used}}(\mathrm{t}) * \mathrm{me} \qquad (18)$$

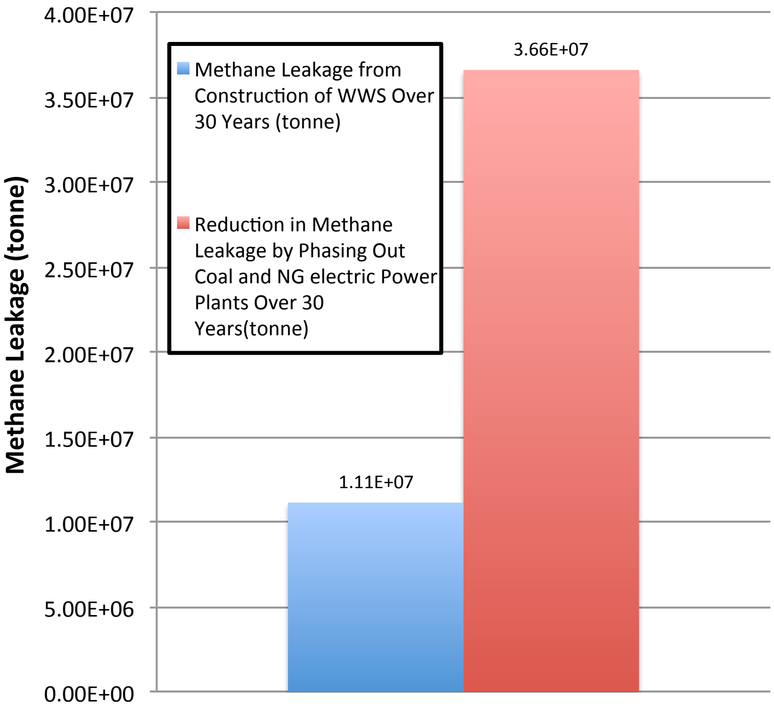


Figure 12. Comparison of Methane Leakage from Construction of WWS and Reduction in Methane Leakage by Phasing Out Coal and NG Electric Power Plants Over 30 Years

3.4 CO_2 EQUIVALENT EMISSIONS REDUCTION

Figures 11 and 12 show that building WWS will reduce GHG emission. To compare the amount of heat trapped by different gases, GWP is used. According to IPCC, GWP for methane in a 20 years time horizon is 86, which means that if the same mass of methane and CO_2 were introduced into the atmosphere, that methane would trap 86 times more heat than CO_2 over the next 20 years [23]. A 100 year GWP is usually used for methane. For this thesis a 20 year GWP was used because it maximizes the estimated impact of methane leakage and therefore ensures that the conclusions are conservative.

The reduction in CO_2 equivalent emission in year t is:

$$\mathrm{CO}_{2\mathrm{eq.}_{\mathrm{red}}}(\mathrm{t}) = \mathrm{CO}_{2_{\mathrm{red}}}(\mathrm{t}) + \mathrm{GWP}_{\mathrm{CH4}} \times \mathrm{CH}_{4_{\mathrm{red}}}(\mathrm{t}) \qquad (19)$$

The CO_2 equivalent emission from construction of WWS in year t is:

$$\mathrm{CO}_{2\mathrm{eq.}_{\mathrm{emit}}}(\mathrm{t}) = \mathrm{CO}_{2_{\mathrm{emit}}}(\mathrm{t}) + \mathrm{GWP}_{\mathrm{CH4}} \times \mathrm{CH}_{4_{\mathrm{emit}}}(\mathrm{t}) \qquad (20)$$

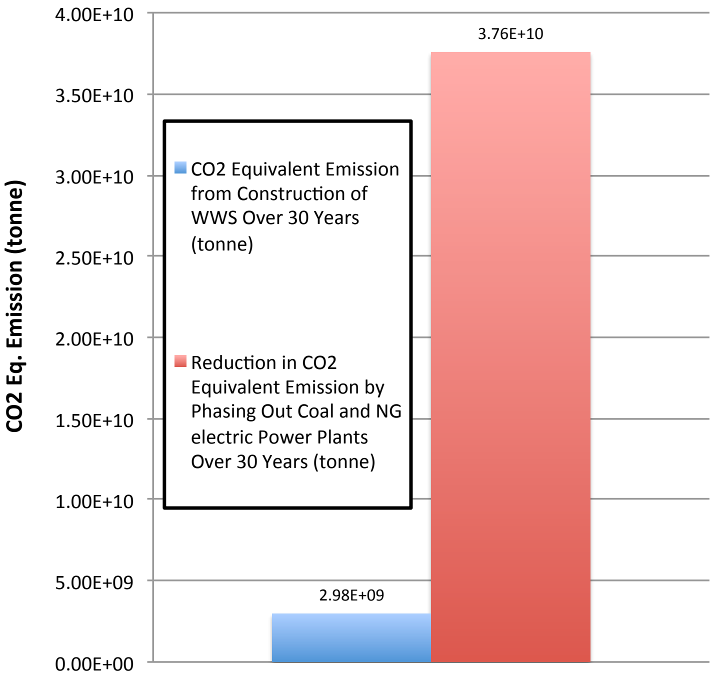


Figure 13. Comparison of CO_2 Equivalent Emission from Construction of WWS and Reduction in CO_2 Equivalent Emission by Phasing Out Coal and NG Electric Power Plants Over 30 Years

Figure 13 shows a comparison of the total CO_2 equivalent emission from construction of a renewable system with the emission reduction by replacing the coal and NG power plants.

The most important conclusion from the analyses in this thesis is that from the energy perspective as well as from the environment perspective, construction of a WWS using natural gas from fracking will yield enormous benefits.

4 ECONOMY ANALYSIS

4.1 CAPITAL COST

This project involves very rapid construction of wind and PV plants. Capital costs for both wind and PV plants are expected to decrease as experience is accumulated. Experience curves, also called learning curves, are widely used to predict cost paths in the mid- to long-term, based on the learning theory. For every doubling of cumulative production/installation, a percentage reduction in costs is expected, called the experience/learning rate [24].

According to Department of Energy (DOE), in the 2011 Wind Technologies Market Report [25], the capacity-weighted average initial capital cost for a wind system was nearly $2.1/W. Photovoltaic (PV) Pricing Trends: Historical, Recent, and Near-Term Projections [26], published by DOE, summarizes a bottom-up modeling analysis of PV system prices. For a ground-mounted utility- scale PV system, the initial capital cost was $2.79/W for fixed-tilt systems.

The current cumulative capacity for wind is 300 GW and the learning rate is 7.2%; the current cumulative capacity for PV is 100 GW and the learning rate is 15% [27,28,29]. Assuming the learning rate will not change in the next 30 years, based on the cumulative capacity calculated above, in the next 30 years, the capital cost for wind and solar will decrease, as shown in Figure 14. Compared with wind, PV has more potential to decrease in capital cost because wind has been in production much longer.

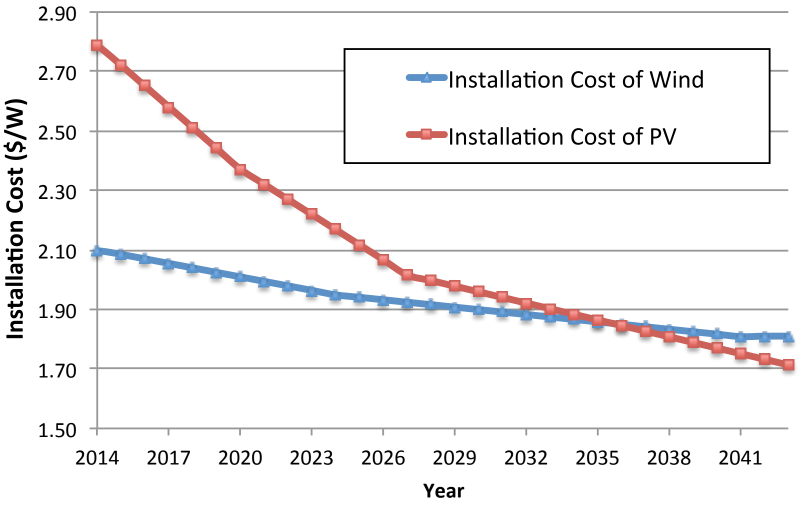


Figure 14. Installation Costs of Wind and PV as a Function of Time

4.2 LEVELIZED COST OF ENERGY

The Cost of Renewable Energy Spreadsheet Tool (CREST) developed by NREL was used to evaluate the economic performance. The CREST model is designed to calculate the Levelized Cost of Energy (LCOE), or minimum revenue per unit of production needed for the modeled renewable energy project to meet its equity investors' assumed minimum required after-tax rate of return [30].

To calculate the LCOE and cash flow, the parameters in Table 4 were used:

Table 4. Parameters for CREST

Items	Units	Value	Reference
Fixed O&M Expense of Wind	$/kW-yr	$11.98	[5]
Fixed O&M Expense of PV	$/kW-yr	$9.92	[5]
% Equity	%	50%	[31]
Required Internal Rate of Return	%	12%	[30]
% Debt	%	50%	[31]
Interest Rate on Term Debt	%	8%	[31]
Debt Term	Year	15	[31]
Federal Income Tax Rate	%	35.0%	[31]

Without considering the transmission and distribution cost, based on the capital cost calculated above using the learning rate, the LCOEs for wind and PV are:

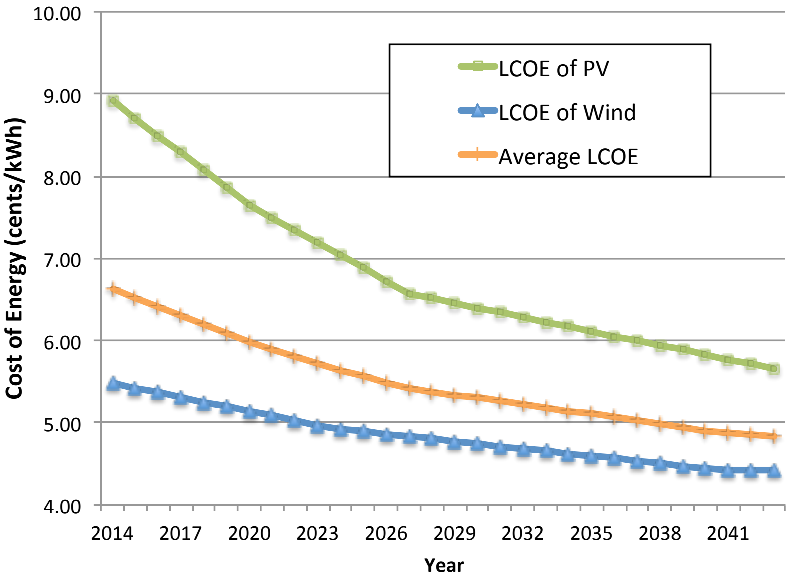


Figure 15. LCOE of Wind, PV and Average LCOE

Since Ca_{wind}:Ca_{PV}=100:71 and capacity factors are know, the power ratio of wind electricity to PV electricity can be calculated. The average cost for the combined wind and solar system for this scenario is shown in Figure 15.

5 CONCLUSIONS AND RECOMMENDATIONS

Based on the analysis in this thesis, the following conclusions are made:

1) Using excess fracked natural gas available from future production one can build a renewable energy system consisting wind and PV that can provide 83% of demand.
2) To avoid a catastrophic drop in production of renewable hardware, a slower rate of transition can provide a reasonably stable production rate if the replacement time of fossil fuels is extended to 30 years.
3) Building WWS has positive environment impacts by decreasing methane leakage and CO_2 emission.
4) The construction can be done in reasonable cost.

Recommendations for a future study are:

1) The types of energy needed to construct wind and PV system requires more detailed analysis.
2) The Short and Diakov study, which was based on data in 2005, should be repeated for the most recent available data.
3) Leakage of methane from natural gas usage should be reduced by proper management and regulations of the causes of leakage.
4) This analysis is restricted to a transition from fossil fuels to renewable for electricity and similar analyses for other energy needs of societies should be made.

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APPENDICES

APPENDIX A: EROI STANDARDIZATION

Different investigators reported different EROIs of the sustainable systems and they had big influence on the result. Table A1 provides EROIs of wind studies.

Table A1. Results of Studies on the EROI for Wind Plants

Year (-)	Original EROI (-)	Capacity factor (-)	Power Rating (MW)	Lifetime (Year)
1998	38.86	0.35	107.25	30
2000	51.30	0.40	0.50	20
2007	34.36	0.23	2.00	20
2008	19.20	0.19	7.26	20
2012	30.59	0.34	2.00	20
2012	27.01	0.24	0.10	25

In these researches, EROIs of wind were calculated as:

$$\mathrm{EROI} = \frac{\mathrm{CF} * \mathrm{Ca} * \mathrm{L}}{\mathrm{e_{wind}} * \mathrm{Ca}}$$

where,

CF is the capacity factor.

Ca is the nameplate capacity of the plant, MW.

L is the lifetime of the plant, year.

$\mathrm{e_{wind}}$is the energy investment per installed capacity, MWh/MW.

The results of these EROI analyses depended on the assumptions used by the investigators. Different assumptions will lead to a big difference of the energy output of a sustainable energy system. To compare those different EROI, it's better to standardize to similar assumptions, operating parameters and boundary assumptions. In this thesis, assuming that CF of wind is 0.35, L is 25 years. So the standardized EROI would be:

Table A2. Standardized EROI for Wind Plants

Year	Original EROI	Standardized EROI
1998	38.86	32.38
2000	51.30	56.11
2007	34.36	65.93
2008	19.20	44.21
2012	30.59	39.24
2012	27.01	39.38

For multi-Si PV,

Table A3. Results of Studies on the EROI for Multi-Si PV Plants

Year	Original EROI	Irradiation ($kWh/m^2/yr$)	Module Efficiency	Performance Ratio	Lifetime (Year)
1995	2.17	1700	0.13	0.75	15
2000	2.75	1700	0.13	0.75	30
2007	2.67	1700	0.14	0.75	20
2008	5.48	1716	0.13	0.78	30
2011	4.58	1700	0.13	0.75	30
2012	5.90	1700	0.13	0.75	30

In these studies, investigators calculated EROI in a different way compared with EROI of wind:

$$\mathrm{EROI} = \frac{h * A * \eta * PR * L}{e_{PV} * A}$$

where,

h is the irradiation, $kWh/m^2/year$.

A is the area of PV panels, m^2.

η is the nominate efficiency of PV panel.

PR is the performance ratio.

L is the lifetime of the system, year.

$e_{pv}$is the energy investment per installed capacity, MWh/m^2.

As discussed for wind, to standardize EROI, assuming that: h is 1700 kWh/m^2/year, η is 13%, PR is 0.75, L is 25 years. So the standardized EROI would be:

Table A4. Standardized EROI for Multi-Si PV Plants

Year	Original EROI	Standardized EROI
1995	2.17	3.62
2000	2.75	2.29
2007	2.67	3.10
2008	5.48	4.42
2011	4.58	3.76
2012	5.90	4.92

In this thesis, to calculate the PV capacity that can be built and electricity output, the capacity factor for PV is assumed to be 0.25.

APPENDIX B: CALCULATION RESULTS

Table B1. Energy Analysis - Comparison of Total Natural Gas Energy from Fracking and Natural Gas Energy Available for Construction

Year	Natural Gas Production from Fracking	NG Energy Available for Construction of WSS
t	P_FNG (t)	E_ava (t)
	GWh	GWh
2014	2.53E+06	6.52E+04
2015	2.60E+06	1.32E+05
2016	2.67E+06	2.01E+05
2017	2.74E+06	2.71E+05
2018	2.81E+06	3.44E+05
2019	2.89E+06	4.18E+05
2020	2.96E+06	4.94E+05
2021	3.04E+06	5.72E+05
2022	3.12E+06	6.53E+05
2023	3.20E+06	7.35E+05
2024	3.29E+06	8.20E+05
2025	3.37E+06	9.06E+05
2026	3.46E+06	9.96E+05
2027	3.55E+06	1.09E+06
2028	3.65E+06	1.18E+06
2029	3.74E+06	1.28E+06
2030	3.84E+06	1.38E+06
2031	3.95E+06	1.48E+06
2032	4.05E+06	1.58E+06
2033	4.16E+06	1.69E+06
2034	4.27E+06	1.80E+06
2035	4.38E+06	1.91E+06
2036	4.49E+06	2.03E+06
2037	4.61E+06	2.15E+06
2038	4.74E+06	2.27E+06
2039	4.86E+06	2.39E+06
2040	4.99E+06	2.52E+06
2041	5.12E+06	2.65E+06
2042	5.26E+06	2.79E+06
2043	5.39E+06	2.93E+06

Table B2. Energy Analysis - Fracked Natural Gas (FNG) Energy Investment and Sustainable Capacity Built

Year	FNG Energy Investment to Wind Plants	FNG Energy Investment to PV Plants	Newly Installed Capacity of Wind Plants in End Year	Newly Installed Capacity of PV Plants in End Year	Total Installed Capacity of Wind Plants in End Year	Total Installed Capacity of PV Plants in End Year
t	E_inv_wind (t)	E_inv_PV (t)	Ca_wind (t)	Ca_PV (t)	Ca_wind_tot (t)	Ca_PV_tot (t)
	GWh	GWh	GW	GW	GW	GW
2014	1.17E+04	5.35E+04	5.98	4.24	5.98	4.24
2015	2.36E+04	1.08E+05	12.11	8.60	18.09	12.84
2016	3.59E+04	1.65E+05	18.41	13.07	36.49	25.91
2017	4.85E+04	2.23E+05	24.87	17.66	61.36	43.57
2018	6.14E+04	2.82E+05	31.50	22.37	92.87	65.93
2019	6.98E+04	3.21E+05	35.79	25.41	128.65	91.34
2020	6.98E+04	3.21E+05	35.79	25.41	164.44	116.75
2021	6.98E+04	3.21E+05	35.79	25.41	200.22	142.16
2022	6.98E+04	3.21E+05	35.79	25.41	236.01	167.57
2023	6.98E+04	3.21E+05	35.79	25.41	271.79	192.97
2024	6.98E+04	3.21E+05	35.79	25.41	307.58	218.38
2025	6.98E+04	3.21E+05	35.79	25.41	343.36	243.79
2026	6.98E+04	3.21E+05	35.79	25.41	379.15	269.20
2027	6.98E+04	3.21E+05	35.79	25.41	414.93	294.60
2028	6.98E+04	3.21E+05	35.79	25.41	450.72	320.01
2029	6.98E+04	3.21E+05	35.79	25.41	486.50	345.42
2030	6.98E+04	3.21E+05	35.79	25.41	522.29	370.83
2031	6.98E+04	3.21E+05	35.79	25.41	558.08	396.23
2032	6.98E+04	3.21E+05	35.79	25.41	593.86	421.64
2033	6.98E+04	3.21E+05	35.79	25.41	629.65	447.05
2034	6.98E+04	3.21E+05	35.79	25.41	665.43	472.46
2035	6.98E+04	3.21E+05	35.79	25.41	701.22	497.86
2036	6.98E+04	3.21E+05	35.79	25.41	737.00	523.27
2037	6.98E+04	3.21E+05	35.79	25.41	772.79	548.68
2038	6.98E+04	3.21E+05	35.79	25.41	808.57	574.09
2039	6.98E+04	3.21E+05	35.79	25.41	838.38	595.25
2040	6.98E+04	3.21E+05	35.79	25.41	862.06	612.06
2041	6.98E+04	3.21E+05	35.79	25.41	879.43	624.40
2042	6.98E+04	3.21E+05	35.79	25.41	890.30	632.11
2043	6.98E+04	3.21E+05	35.79	25.41	894.58	635.15

Table B3. Energy Analysis - Sustainable Electricity Generation and Primary Energy Reduction

Year	Total WWS Electricity Energy Generation Per Year	Electricity Demand in U.S.	WWS Electricity Share of Total Demand	Reduction in Primary Energy Use by Replacing the Fossil Powered Plants
t	E_ele_PV (t)	E_demand (t)	p	E_red(t)
	GWh	GWh	-	GWh
2014	0.00E+00	3.82E+06	0.0%	0.00E+00
2015	2.76E+04	3.86E+06	0.7%	5.13E+04
2016	8.36E+04	3.89E+06	2.1%	1.55E+05
2017	1.69E+05	3.93E+06	4.3%	3.13E+05
2018	2.84E+05	3.96E+06	7.2%	5.27E+05
2019	4.29E+05	4.00E+06	10.7%	7.97E+05
2020	5.94E+05	4.03E+06	14.7%	1.10E+06
2021	7.60E+05	4.07E+06	18.7%	1.41E+06
2022	9.25E+05	4.11E+06	22.5%	1.72E+06
2023	1.09E+06	4.14E+06	26.3%	2.03E+06
2024	1.26E+06	4.18E+06	30.0%	2.33E+06
2025	1.42E+06	4.22E+06	33.7%	2.64E+06
2026	1.59E+06	4.26E+06	37.3%	2.95E+06
2027	1.75E+06	4.29E+06	40.8%	3.25E+06
2028	1.92E+06	4.33E+06	44.2%	3.56E+06
2029	2.08E+06	4.37E+06	47.6%	3.87E+06
2030	2.25E+06	4.41E+06	51.0%	4.18E+06
2031	2.41E+06	4.45E+06	54.2%	4.48E+06
2032	2.58E+06	4.49E+06	57.4%	4.79E+06
2033	2.74E+06	4.53E+06	60.6%	5.10E+06
2034	2.91E+06	4.57E+06	63.6%	5.41E+06
2035	3.07E+06	4.61E+06	66.6%	5.71E+06
2036	3.24E+06	4.66E+06	69.6%	6.02E+06
2037	3.41E+06	4.70E+06	72.5%	6.33E+06
2038	3.57E+06	4.74E+06	75.3%	6.63E+06
2039	3.74E+06	4.78E+06	78.1%	6.94E+06
2040	3.87E+06	4.83E+06	80.3%	7.20E+06
2041	3.98E+06	4.87E+06	81.8%	7.40E+06
2042	4.06E+06	4.91E+06	82.7%	7.55E+06
2043	4.11E+06	4.96E+06	83.0%	7.64E+06

Table B4. Environmental Impacts - GHG Emission and Reduction

Year	CO_2 Emission from Construction of WWS	Reduction in CO_2 Emission by Replacing Fossil Powered Plants	Methane Leakage from Construction of WWS	Reduction in Methane Leakage by Replacing NG Power Plants	CO_2 Equivalent Emission from Construction of WWS	Reduction in CO_2 Equivalent Emission by Replacing Fossil Powered Plants
t	CO_2_emit (t)	CO_2_red (t)	CH_4_emit (t)	CH_4_red (t)	CO_2_eq._emit (t)	CO_2_eq._red (t)
	tonne	tonne	tonne	tonne	tonne	tonne
2014	1.18E+07	0.00E+00	6.50E+04	0.00E+00	1.74E+07	0.00E+00
2015	2.39E+07	1.47E+07	1.32E+05	1.57E+04	3.53E+07	1.61E+07
2016	3.64E+07	4.46E+07	2.00E+05	4.75E+04	5.36E+07	4.87E+07
2017	4.91E+07	9.00E+07	2.71E+05	9.58E+04	7.24E+07	9.83E+07
2018	6.22E+07	1.51E+08	3.43E+05	1.61E+05	9.17E+07	1.65E+08
2019	7.07E+07	2.29E+08	3.89E+05	2.44E+05	1.04E+08	2.50E+08
2020	7.07E+07	3.17E+08	3.89E+05	3.38E+05	1.04E+08	3.46E+08
2021	7.07E+07	4.06E+08	3.89E+05	4.32E+05	1.04E+08	4.43E+08
2022	7.07E+07	4.94E+08	3.89E+05	5.26E+05	1.04E+08	5.39E+08
2023	7.07E+07	5.82E+08	3.89E+05	6.19E+05	1.04E+08	6.36E+08
2024	7.07E+07	6.71E+08	3.89E+05	7.13E+05	1.04E+08	7.32E+08
2025	7.07E+07	7.59E+08	3.89E+05	8.07E+05	1.04E+08	8.28E+08
2026	7.07E+07	8.47E+08	3.89E+05	9.01E+05	1.04E+08	9.25E+08
2027	7.07E+07	9.36E+08	3.89E+05	9.95E+05	1.04E+08	1.02E+09
2028	7.07E+07	1.02E+09	3.89E+05	1.09E+06	1.04E+08	1.12E+09
2029	7.07E+07	1.11E+09	3.89E+05	1.18E+06	1.04E+08	1.21E+09
2030	7.07E+07	1.20E+09	3.89E+05	1.28E+06	1.04E+08	1.31E+09
2031	7.07E+07	1.29E+09	3.89E+05	1.37E+06	1.04E+08	1.41E+09
2032	7.07E+07	1.38E+09	3.89E+05	1.46E+06	1.04E+08	1.50E+09
2033	7.07E+07	1.47E+09	3.89E+05	1.56E+06	1.04E+08	1.60E+09
2034	7.07E+07	1.55E+09	3.89E+05	1.65E+06	1.04E+08	1.70E+09
2035	7.07E+07	1.64E+09	3.89E+05	1.75E+06	1.04E+08	1.79E+09
2036	7.07E+07	1.73E+09	3.89E+05	1.84E+06	1.04E+08	1.89E+09
2037	7.07E+07	1.82E+09	3.89E+05	1.93E+06	1.04E+08	1.98E+09
2038	7.07E+07	1.91E+09	3.89E+05	2.03E+06	1.04E+08	2.08E+09
2039	7.07E+07	2.00E+09	3.89E+05	2.12E+06	1.04E+08	2.18E+09
2040	7.07E+07	2.07E+09	3.89E+05	2.20E+06	1.04E+08	2.26E+09
2041	7.07E+07	2.13E+09	3.89E+05	2.26E+06	1.04E+08	2.32E+09
2042	7.07E+07	2.17E+09	3.89E+05	2.31E+06	1.04E+08	2.37E+09
2043	7.07E+07	2.20E+09	3.89E+05	2.34E+06	1.04E+08	2.40E+09

Table B5. Economy Analysis – Installation Cost and Levelized Cost of Energy Reduction

Year	Installation Cost of Wind	Installation Cost of PV	LCOE of Wind	LCOE of PV	Average LCOE
t	Cost_wind (t)	Cost_PV (t)	LCOE_wind (t)	LCOE_PV (t)	LCOE_ave (t)
	$/W	$/W	cents/kWh	cents/kWh	cents/kWh
2014	2.10	2.79	5.48	8.93	6.64
2015	2.08	2.72	5.42	8.72	6.53
2016	2.07	2.65	5.37	8.50	6.42
2017	2.05	2.58	5.31	8.29	6.31
2018	2.04	2.51	5.26	8.08	6.20
2019	2.02	2.44	5.20	7.87	6.09
2020	2.01	2.37	5.15	7.66	5.99
2021	1.99	2.32	5.09	7.50	5.90
2022	1.98	2.27	5.04	7.35	5.81
2023	1.96	2.22	4.98	7.19	5.72
2024	1.95	2.17	4.93	7.04	5.64
2025	1.94	2.12	4.90	6.89	5.56
2026	1.93	2.07	4.87	6.73	5.49
2027	1.92	2.02	4.84	6.58	5.42
2028	1.92	2.00	4.81	6.52	5.38
2029	1.91	1.98	4.78	6.46	5.34
2030	1.90	1.96	4.75	6.40	5.30
2031	1.89	1.94	4.72	6.35	5.26
2032	1.88	1.92	4.69	6.29	5.22
2033	1.87	1.90	4.66	6.23	5.18
2034	1.87	1.88	4.63	6.18	5.15
2035	1.86	1.86	4.60	6.12	5.11
2036	1.85	1.85	4.57	6.06	5.07
2037	1.84	1.83	4.54	6.00	5.03
2038	1.83	1.81	4.51	5.95	4.99
2039	1.82	1.79	4.48	5.89	4.95
2040	1.82	1.77	4.45	5.83	4.91
2041	1.81	1.75	4.42	5.77	4.87
2042	1.81	1.73	4.42	5.72	4.85
2043	1.81	1.71	4.42	5.66	4.83