The Potential for Fusion Power to Mitigate U.S. Greenhouse Gas Emissions

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THE POTENTIAL FOR FUSION POWER TO MITIGATE U.S. GREENHOUSE GAS EMISSIONS

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ABSTRACT

This study summarizes a recent life-cycle net energy analysis (NEA) on a modern natural gas turbine power plant for comparison against DT fusion and conventional technologies (coal, fission, and wind). The NEA results are used as the basis for developing a life-cycle greenhouse gas (GHG) emission rate. The GHG emission rate for DT fusion is 9 metric tonnes of CO_2 equivalent emitted per gigawatt electric hour produced (T/GW_eh). This rate compares favorably against gas turbine (464 T/GW_eh) and conventional coal (974 T/GW_eh), and competitively against fission (15 T/GW_eh) and wind (15 T/GW_eh). The implications of this research for U.S. GHG mitigation are discussed. In evaluated scenarios, the installed nuclear and renewable capacity in the U.S. must quadruple by 2050 to maintain a Kyoto based emission target, with fusion and/or other renewable sources comprising 43-59% of U.S. capacity.

I. INTRODUCTION

Scientific opinion on climate change has reached a new level of concern. "It is not a question of whether the Earth's climate will change, but rather when, where and by how much", states Robert Watson, Chairman of the Intergovernmental Panel on Climate Change (IPCC). [1] There is clear evidence that changes in climate variability indicators have already occurred. Global mean surface temperature has increased by between 0.3-0.6°C since the late 19th century.[1] In addition, global sea levels have risen by between 10-25 cm during the same period; much of which may be related to the temperature increase.[1] According to the IPCC, these changes are "unlikely to be entirely natural in origin." The balance of evidence suggests an identifiable human influence on global climate.[2]

Recent analyses project future increases in high-temperature extremes, decreases in low-temperature extremes, and increases in intense precipitation events.[3] Potential consequences of such climate changes include droughts, floods, and disease, as well as distress to critical ecosystems and agricultural areas around the world.[2]

U.S. electricity generation is the largest domestic source of GHG, accounting for about 40% of national emissions and 10% of global emissions.[4] While clean technologies such as fusion aspire to meet our long-term electricity needs, natural gas is considered by many as an intermediate, lower-emission alternative. Natural gas is the fastest growing fuel for U.S. electricity generation, increasing over 40% since 1990.[5] Gas generation currently comprises only about 15% of the current electricity mix, but it is expected to provide the majority of the new electrical capacity for the next 20 years. The Energy Information Agency projects that 90% of an estimated 1,000 new generating plants installed by 2020 will be combined cycle or combustion turbine technology fueled by natural gas, or both oil and gas.[6]

II. GAS TURBINE LIFE-CYCLE

The gas turbine power plant life-cycle analysis includes natural gas production and transmission, fabrication of equipment and structural materials, plant construction, operation, and decommissioning. The power plant used as the basis for this study is a 2 x 1 combined cycle combustion turbine plant.[7]

The Energy Payback Ratio (EPR) is a comparison of the useful energy output of a system to the total energy consumed by the system over its life-cycle. Determining the energy inputs is a rigorous process that employs two basic methods called Input/Output (I/O) and Process Chain Analysis (PCA). The Input/Output (I/O) method correlates dollar cost to energy use.[8] PCA evaluates the material and energy flows for each process within the system life-cycle.[9] Most of the energy requirements for the gas turbine life-cycle were estimated using the PCA method, while the I/O method was used to complete some portions of the life-cycle. The energy investment in the gas turbine life cycle is normalized to an output of one GW_e full-power year (GW_ey) to allow for comparison against alternative technologies (Table 1).

The gas turbine life-cycle has a much higher normalized energy investment than alternative technologies, primarily due to the energy invested during the fuel cycle. For every ten cubic feet of natural gas delivered to the power plant, one cubic foot is consumed for production, processing, and transmission.[10] This massive energy investment comprises 97% of the life-cycle energy inputs for the gas turbine and dramatically limits the energy payback ratio. The remainder of the life-cycle analysis (plant construction, operation, decommissioning) accounts for only about 3% of the total energy inputs.

Gas turbine, coal, and fission life-cycles are similar in that the majority of energy investment is associated with the fuel cycle. The largest energy inputs to the gas turbine fuel cycle are venting and flaring during natural gas production, as well as the use of natural gas to power production and transmission compressors.[7] About two-thirds of the energy required for the coal fuel cycle is consumed during rail transportation and about one-third is consumed during mining.[11] The fission analysis is for a light water reactor, which requires a significant energy investment in fuel enrichment.[11] Fusion and wind power plants have little and no energy investment in the fuel cycle respectively, but have a higher proportion of energy input associated with plant construction.[11]

By convention, NEA excludes the energy content of natural gas consumed at the plant turbines. So while the modern gas turbine plant operates with a significantly higher thermal efficiency (50%) than the conventional coal plant (32%), this advantage does not result in a better EPR. Instead, the gas turbine has a lower EPR due to the less efficient natural gas fuel cycle. However, the benefit of the higher thermal efficiency is reflected by the calculation of the GHG emission rate that includes emissions from the plant.

The energy requirements calculated for each phase of the life cycle were used to estimate corresponding GHG emissions. Unlike the NEA, GHG estimates also include emissions from fuel consumed at the plant turbines. For this study, the life-cycle emissions are normalized in terms of tonnes CO_2-equivalent emitted per gigawatt-hour of electricity produced (T/GW_eh), allowing for comparison against alternative technologies (Table 2). While the gas turbine emission rate is 48% of the coal emission rate, both fossil fuel technologies have significantly higher emission rates than the non-fossil fuel technologies.

Table 1. Normalized Energy Investments Made in Generating Electricity (TJ_{th}/GW_ey)

Process	Natural Gas	DT Fusion[10]	Coal[10]	Fission[10]	*Wind[10]
Fuel Related	7,327	48	2,318	1,299	0
Materials & Construction	90	604	147	195	875
Operation & Maintenance	323	435	440	239	489
Decommissioning	3	71	20	191	50
Total Normalized Energy Investment	7,743	1,158	2,925	1,923	1,414
Energy Payback Ratio (EPR)**	4	27	11	16	23

*Wind analysis excludes energy storage.

** Energy Payback Ratio is calculated by dividing one gigawatt electric year output (31,536 TJ_{th}) by the total normalized energy investment. For natural gas, EPR = (31,536 TJ_{th}/GW_ey) / (7,743 TJ_{th}/GW_ey) ≈ 4.

Table 2. Normalized Greenhouse Gas Emission Rate (Tonnes CO_2-equivalent/GW_eh)

Process	Natural Gas	DT Fusion[10]	Coal[10]	Fission[10]	*Wind[10]
Fuel Related	77	0.4	17	10	0
Materials & Construction	1	5.5	1	2	10.2
Operation & Maintenance	386	3	956	2	4
Decommissioning	.02	0.4	0.2	1	0.4
Total Emission Rate	464	9	974	15	15

*Wind analysis excludes energy storage.

Fuel consumed during operation is the largest contributor to the GHG emission rate for the gas turbine life cycle, accounting for 82% of emissions (382 T/GW_eh). The fuel cycle contributes 17% of the life-cycle emissions (77 T/GW_eh). Plant materials, construction, maintenance, and decommissioning comprise the remaining 1% (5 T/GW_eh).

Of the 77 T/GW_eh of CO_2-equivalent emissions attributed to the gas turbine fuel cycle, 40 T/GW_eh are the result of methane leaks.[7] Estimates of methane leakage from the natural gas fuel cycle vary greatly, with most of the commonly cited estimates ranging from 1% - 4% of production.[12] This study utilized U.S. EPA estimates of methane emissions, which correspond to a 1.4% leakage rate.[13] Because methane has 21 times the global warming potential of CO_2, the assumed leakage rate has a significant impact on life-cycle emissions.[2] Methane losses occurring during coal mining are not included in Table 2. Incorporating methane losses would increase the fuel related coal emissions by about 25 T/GW_eh.[13,14]

III. U.S. POLICY IMPLICATIONS

The U.S. is the world's largest anthropogenic GHG contributor.[15] U.S. electricity generation (the largest domestic source of GHG) produces about 40% of total national emissions and 10% of total global emissions.[4] In December 1997, representatives from more than 160 countries met in Kyoto, Japan, and negotiated binding limits on GHG emissions for developed nations. The Kyoto target for the U.S. is 7% below 1990 levels on average over a commitment period from 2008 to 2012. Although the U.S. has not ratified the Kyoto Agreement, this agreement does provide a benchmark for measuring potential mitigation measures.

If the U.S. accepts the Kyoto assigned emission target and implements it evenly across all sectors of the economy (i.e., electric utilities are required to reduce emissions to 7% below 1990 levels), then one is left with an interesting question: "What mix of generating technologies is necessary to meet both the emission target and projected electricity demand?" The following section uses the Kyoto emission target as a long-term goal. Under this assumption, fusion energy and other low-emission technologies have enormous potential for GHG mitigation over the next 50 years.

IV. SCENARIOS FOR MEETING EMISSION TARGETS

For the U.S. electric industry to effectively meet a GHG reduction target will require reducing emissions while still meeting the growing demand for electricity. Figure 1 uses a ternary phase diagram to illustrate the distribution of generating technologies needed to maintain the Kyoto target with 1.3% annual electricity growth[16] extended through 2050.

The inputs to the ternary plot include life-cycle emission rates,[7,11,17] electricity demand, and a GHG emission target. At successive time intervals, an electricity supply distribution line is plotted that satisfies the input requirements. Each point on the line represents a specific supply distribution (i.e., % from coal, % from gas/oil, % from nuclear/renewable) that meets both the electricity demand and the Kyoto emission target. Figure 1 accounts for fuel switching only and neglects other mitigating measures such as sequestration or fuel efficiency improvements.

Scenarios C and D are of interest, as they illustrate converting generating capacity away from coal, and towards gas/oil and nuclear/renewable (N/R) respectively. Meeting the Kyoto target by switching to gas/oil (Scenario C) would require complete replacement of coal by 2011, after which N/R would have to replace gas/oil to maintain target emissions (Figure 2). Meeting the Kyoto target by switching to N/R (Scenario D) would require at least 53% N/R by 2010, and 73% N/R by 2050 (Figure 3). Compared to 1999, the N/R capacity increases almost 400% by 2050 under Scenario C and almost 500% by 2050 under Scenario D.

The implications for fusion energy are dramatic if one assumes that the net amount of electricity from fission and hydro does not change from 1999 levels (Figure 4). The other N/R technologies (fusion, solar, wind) would be required to generate 3.1 x 10^6 $GW_e h$ in 2050 under Scenario C, or 43% of the total U.S. capacity. Under Scenario D, the other N/R technologies need to generate 4.2 x 10^6 $GW_e h$ in 2050, or 59% of the total U.S. capacity.

While fusion energy may have a lower life-cycle emission rate than wind or solar technologies, the emissions from any of these technologies are small when compared to fossil fuels.[11,17] However, fusion may be preferred over solar and wind technologies for applications requiring uninterrupted base-load supply. Fusion also offers advantages over fission because it reduces long-lived radioactive waste and is not a viable technology for nuclear weapons proliferation.

Figure 1. Kyoto emission target compliance scenarios

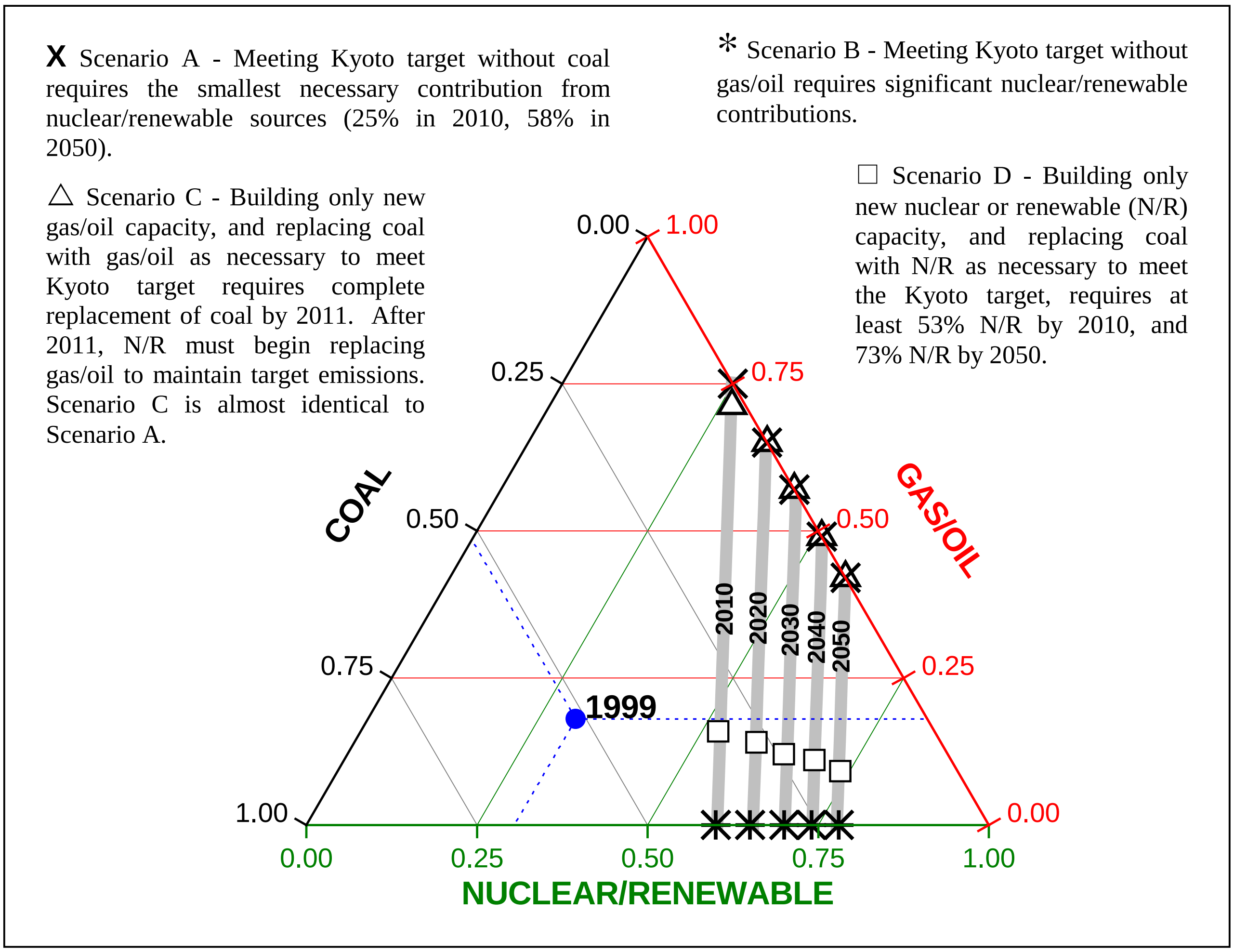


Figure 2. Scenario C – Converting from coal to gas/oil for U.S. Kyoto target compliance (GW_ehx10^6)

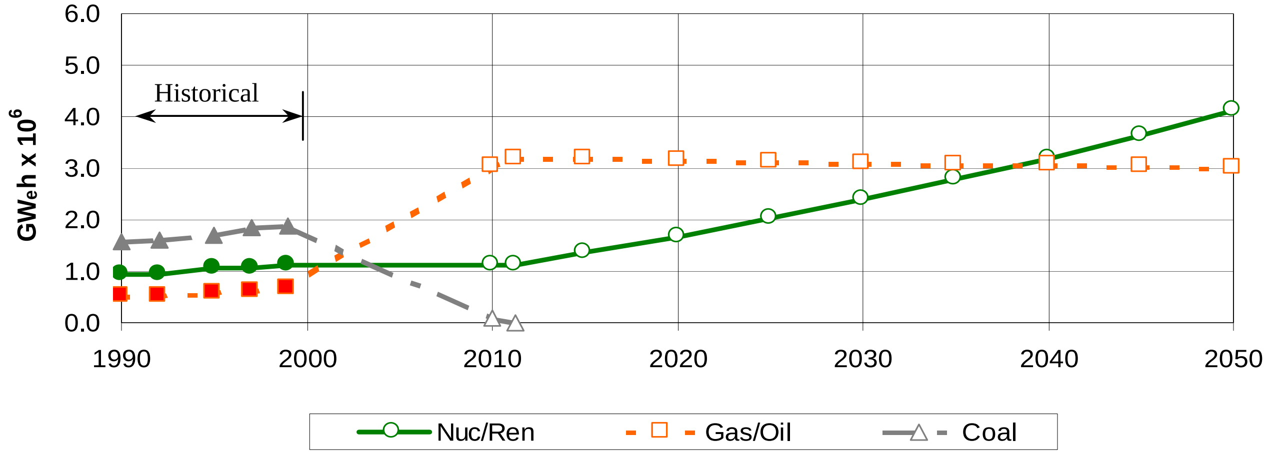


Figure 3. Scenario D – Converting from coal to nuclear/renewable for U.S. Kyoto target compliance (GW_ehx10^6)

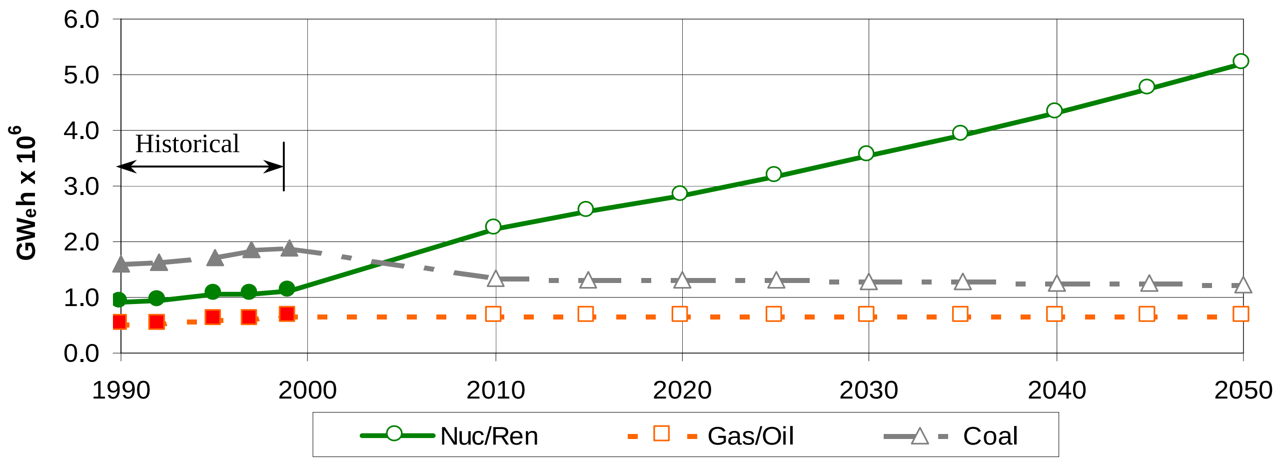
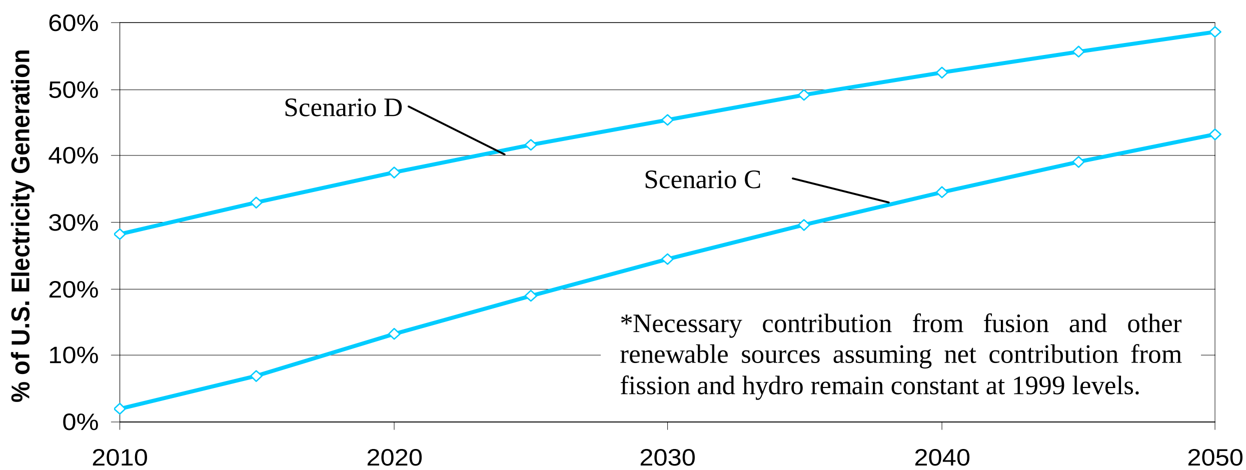


Figure 4. Fusion/renewable contribution for Kyoto emission target compliance*



V. CONCLUSION

Gas turbine technology can provide an effective means of meeting the Kyoto-based GHG emission target only if coupled with significant contributions from nuclear and renewable technologies. Absent the nuclear/renewable contribution, major carbon sequestration and energy conservation efforts would be required to meet even modest GHG reduction goals. Maintaining the Kyoto-based emission target requires significant contributions from fusion and other renewable sources by 2050 (43-59% of the U.S. production). This assumes modest electricity growth (1.3% per year) and constant contributions from fission and hydro (10^6 $GW_e h$/year).

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