Assessment of Market Potential of Conventional and Unconventional Fusion Reactors

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Introduction

Due to growing concerns about global warming and energy security,[1] the energy market is beginning to transform and will likely be very different in half a decade. There are many developing technologies and ideas about where should the energy market head. Among them is fusion energy. Commonly referred to as the "energy source of the stars," fusion energy is being developed in two fairly different paths: the conventional path, based on very large reactors, and the unconventional path, based on small reactors. The goal of this report is to examine potential trends in the energy market and to assess the future market potential of both fusion technologies. The assessment includes "hidden" benefits, particularly positive effects on fossil-fuel exporting countries.

Fusion Energy

Fusion energy is the energy produced when lighter elements are "fused" together to make heavier ones.[2] When this nuclear reaction happens in stars, including our sun, it occurs between varieties of elements. However, physicists have determined that on earth the reaction is most feasible between deuterium and tritium, even though other elements are still considered. Both deuterium and tritium are isotopes of hydrogen; deuterium can be found in water, while tritium can be produced from lithium, an abundant element. Thus, the fuel for a nuclear fusion reaction is virtually unlimited, unlike fossil fuels or uranium that is used in nuclear fission reactions.[3]

The fusion reaction entails deuterium and tritium fusing and producing helium and a neutron. The mass of the initial elements is slightly larger than the mass of the output elements; the access mass is transformed into energy via Einstein famous $E=MC^2$ formula. Considering the elements are moving at very high speeds, exceeding ten million meters per second, when they fuse, energy released from a reaction that involves a tiny amount of mass is comparable to the energy released from three hundred gallons of gasoline. However, sustaining a nuclear fusion reaction is difficult. The problem is that there are two interacting forces between the deuterium and tritium elements: a strong nuclear force that binds nuclei together at subatomic distances as well as a electrometric force that pushes them apart because they are of the same charge. To overcome the electromagnetic force, the elements must collide at very high speeds. Since motion is heat, the deuterium-tritium gas mixture – a plasma – must at a temperature of 100 million of degrees Celsius. The main challenge of fusion research is to sustain the nuclear reaction for a long period of time, while maintaining the plasma at very high temperature. The later of the two requirements has been achieved at a greater success rate than the former.[4]

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[1] Manav Tanneeru. "Have we reached the energy tipping point?" *CNN*, July 9, 2007, via http://www.cnn.com.
[2] Robert Goldston et al.."A Plan for the Development of Fusion Energy," *Journal of Fusion Energy* 21.61 (2002), 61-111.
[3] T. Kenneth Fowler, *The Fusion Quest* (Baltimore: John Hopkins University Press, 1997).
[4] Ibid.

Fusion research began in the early 1950s in the United States, Britain, and the Soviet Union. It was classified until 1958, afterwards becoming a massive international collaboration. In the early years, physicists pursuing magnetic fusion – a method of confining plasma with magnetic fields - invented a variety of reactor designs. In 1968, scientists in Russia designed the T-3 Tokamak reactor that proved to perform considerably better than the competition. Following the success, tokamaks became the primary focus of fusion research, internationally, while other reactor designs were studied less. In 1994, the Tokamak Fusion Test Reactor (TFTR) in the Princeton Plasma Physics Laboratory produced 10.67 megawatts of power. This result signaled that fusion is in fact an achievable undertaking. The next major step in tokamak-based magnetic fusion is the completion of the ITER, an internationally designed and funded reactor that is projected to output as much power as a commercial fusion power plant. The ITER is expected to be complete by 2016. Parallel to work done on the ITER, there is a revival of research into other magnetic fusion reactor designs.[5]

Branching off thermonuclear research was the idea that little pellets of deuterium and tritium (DT) could be heated to a point when they will produce small explosions of energy without the use of nuclear fission reaction for the ignition process, as was the case in the hydrogen bomb. Following the invention of lasers in the late 1950s, scientists started researching ways to create explosions and contain the energy, using lasers to compress and heat DT pellets. This method, called inertial fusion, has been developing at a quick pace, despite the fact that much of the research was classified until the early 1990s. The main difficulty of achieving energy confinement using inertial fusion is having a laser that releases enough energy to compress and heat adequately large DT pellets. The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory leads the research for development of such lasers, while trying to maintain their economic competitiveness.[6] Giving time constrains, this report does not explore further into inertial fusion.

Fusion energy possesses multiple benefits that make it one of the most promising sustainable energy sources for the future. The fuel used in fusion reactions is virtually unlimited and the reaction itself does not release carbon emissions. Fusion power plants are projected to produce considerably less radioactive waste and to be significantly safer than fission power plants.

Conventional Path to Commercial Fusion Energy

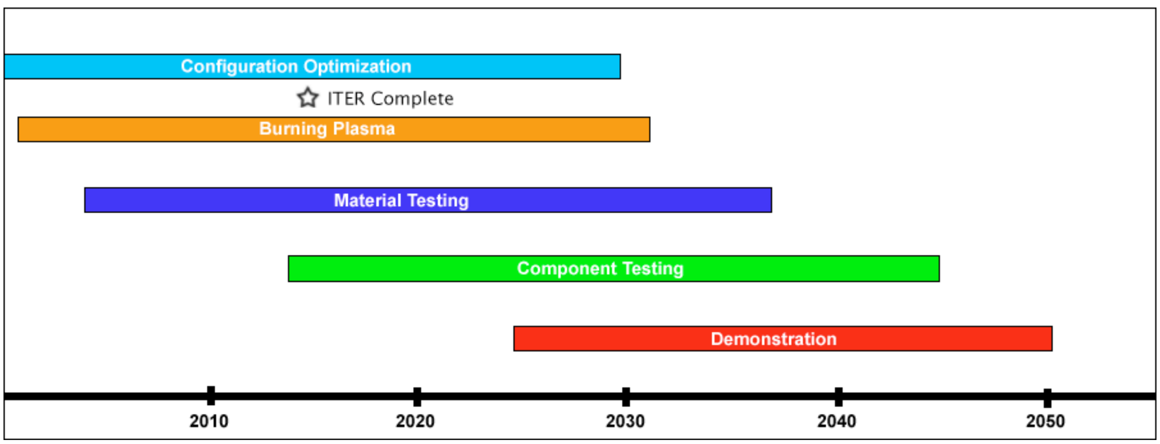
The majority of magnetic fusion research has been focused on tokamaks and other reactor designs with low self-organization complexity. Due to natural constrains, these reactors must be very large. For instance, the ITER is specified to have an eight-meter

[5] John Holdren et al. "The U.S. Program of Fusion Energy Research and Development: Report of the Fusion Review Panel of the President's Council of Advisors on Science and Technology," *Journal of Fusion Energy* 14.2 (1995), 213-250.
[6] Holdren et al. "Report."

outer radius and a four-meter inner radius.[7] The construction for it will take ten years at a cost of five billion Euros (about 6.8 billion dollars).[8] Since the construction of new full-size_reactors for experimentation is extremely costly and lengthy, the entire research and development effort behind magnetic fusion is a decades long process.

Assuming current level of funding, the nominal duration estimates for magnetic fusion, based on tokamak or other conventional reactor designs, to emerge as a commercially viable source of energy range between 50 to 70 years (Figure 1). The Plan for the Development of Fusion Energy,[9] endorsed by President George W. Bush, projects that within 35 years a demonstration fusion power plant (a Demo) will be built. This plan assumes five stages of research and development that will lead up and influence the demo: configuration optimization, burning plasma, materials testing, component testing, and demonstration. Currently, fusion research is still on the first stage. The United States will pursue two major paths of development. One will be centered on the ITER, while the other will be based on domestic research both on tokamak and non-tokamak reactor designs. The Demo will be constructed based on the "best" reactor design.

Figure 1:
Timeline for Conventional Magnetic Fusion Development*



* Source: Goldston et al. "A Plan for the Development of Fusion Energy"

In this scenario, a commercial magnetic fusion reactor will be comparable to one of the reactor designs analyzed by a Department of Energy commissioned report[10] chaired by Prof. John Holdren.

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[7] Emilio Panarella, "On the Ignition of the ITER Machine," American Physics Society. http://flux.aps.org/meetings/YR97/BAPSDPP97/abs/S500008.html (accessed on October 13, 2007).
[8] ITER Project, "ITER Introduction," ITER Project. http://www.iter.org/a/n1/introduction.htm (accessed on October 13, 2007).
[9] Goldston et al. "Plan."
[10] Holdren et al. "Report."

The following is a set of four fusion tokamak reactors that sample a large range possible construction and operation costs:

1. V-Li/TOK – D-T fusion reactor using a tokamak configuration, with vanadium-alloy structure and liquid lithium as coolant/breeder.

2. V-Li/RFP - High-power-density reactor with a RAF structure with a V-Li blanket minimally modified from V-Li/TOK.

3. Si/C-He/TOK – Low activation tokamak with silicon carbide (SiC) structure, helium coolant, and Li_2O breeder.

4. V-D^3He/TOK – Advanced fuel, water-cooled tokamak based on D-^3He fuel cycle.[11]

For comparison, the following are two nuclear fission reactors, a modern reactor design and a developing reactor design:

1. PWR-BPE – Westinghouse pressurized water reactor – currently used, Generation II reactor.

2. PRISM – General Electric Power Reactor Inherently Safe Module breeder reactor[12] – Generation IV reactor – to be commercial by 2030s.[13]

The direct cost of materials, indirect cost of construction[14], maintenance costs, fuel costs, and waste management cost sum to the total cost of construction and operation of nuclear power plants. These costs are heavily influenced by the amount of active and passive design features present in each power plant. Active design features are features that are employed solely to provide safety, while passive design features are features that provide safety, but are also crucial to the reactor designs. Not only do passive design features generally provide more safety than active ones, but active features also drive up the costs of the power plants. Fission plants require many active design features that considerably markup their cost of energy. On the other hand, fusion power plants are expected to rely more on passive design features.

Another influence on the cost is management of radioactive waste. Waste from nuclear fission power plants has to be specially stored, likely buried in deep geological storages. While currently the costs of waste management only slightly markup the cost of plant operations, as reflected in the presented cost estimations, in the long run, these costs are likely to grow due to the difficulty of managing larger amounts of existing waste. In

[11] John Holdren et al. “Exploring the Competitive Potential of Magnetic Fusion Energy: The Interaction of Economics with Safety and Environmental Characteristics,” *Fusion Technology* 13 (Jan. 1988), 7-56.
[12] Holdren et al., “Overview.”
[13] John Sheffield and Steve Obenschain. “Energy Options for the Future: Summary of Presentations,” Joint Institute for Energy & Environment Report, 2004. http://sunsite.utk.edu/jiee/pdf/2004_05energyoptions.pdf.
[14] Namely, associated indirect costs, contingency, and interest during construction (assuming it takes six years to construct a power plant).

contrast, fusion produces less radioactive waste, whose radioactivity is expected to be small enough to qualify for shallow burial, a process much cheaper than the one required for fission waste.

Based on the radioactive danger in case of accidents, workers and public exposure to radiation in routine operation, and radioactive waste management, the following table displays safety assurance needs for each reactor design. The safety assurance primarily reflects the amount of active safety features needed for each reactor design:

Figure 2:
Levels of Safety Assurance*

Case	Optimistic Concept Evaluation	Nominal Design Estimate	Conservative Concept Evaluation
1. V-Li/TOK	2	3	4
2. V-Li/RFP	3	4	4
3. SiC-He/TOK	1	1	2
4. V-D^3He/TOK	1	2	2
5. PWR-BPE	4	4	4
6. PRISM	3	3	4

*Source: Holdren et al. "The Competitive Potential of Magnetic Fusion Energy"

Based on these safety evaluations, the following is projected costs of energy (COE) of the reactor designs:

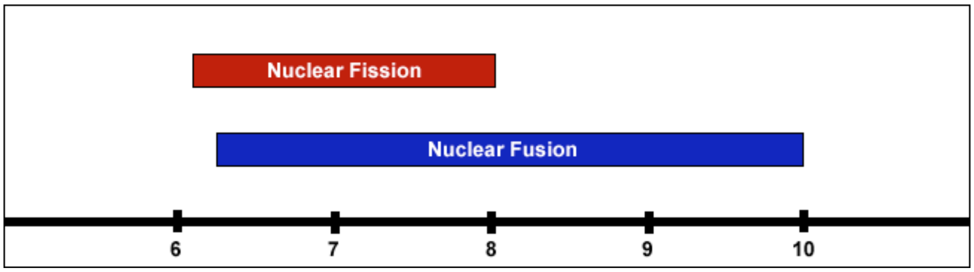
Figure 3:
COE (cents/kWh) with Safety Assurance Credits*[a]

Case	Optimistic Concept Evaluation	Nominal Design Estimate	Conservative Concept Evaluation	No Safety Assurance Credits[b]
1. V-Li/TOK	8.3	9.0	9.7	9.7
2. V-Li/RFP	6.4	6.8	6.8	6.8
3. SiC-He/TOK	7.3	7.3	8.6	10.00
4. V-D^3He/TOK	6.3	7.5	7.5	8.7
5. PWR-BPE	-	-	-	6.1
6. PRISM	-	-	-	8.0

*Source: Holdren et al. "The Competitive Potential of Magnetic Fusion Energy." Prices updated from 1986 to 2007 dollars, via annual average inflation rates from http://www.inflationdata.com.
[a] Assumes lifetime of power plant is 30 years, but doesn't discount costs.
[b] Assumes that as many active safety features needed as in modern nuclear fission power plants. Also, assumes constant rate of .1 cent/kWh for radioactive waste management.

While range of the cost of fusion is greater than the one for fission, fusion may be only slightly more expensive than nuclear fission (Figure 4).

Figure 4:
COE (cents/kWh) Comparison of Fission and Fusion Plants



A major concern about nuclear fission power plants is that they may increase risk of nuclear proliferation, since their waste could be used to produce nuclear weapons. Tritium waste, natural to fusion reactors, could also be used for weapons. However, the technology that allows such utilization is considerably more complicated and secret than the one that employs uranium waste, natural to fission reactors. Fusion reactors could be fed materials other than tritium, which would generate waste more appropriate for weapons. However, such conversions would be easily noticeable by inspectors, whereas utilization of uranium waste from fission power plants could be more easily disguised.

Alternate Path to Commercial Fusion Energy

An alternative path to mainstream magnetic fusion development is based on Field-Reversed Configuration (FRC) reactor designs. The FRC reactor design has high power density, a simple structure, and a simple magnetic topology.[15] A typical FRC reactor is very small. For example, a test reactor in the University of Washington has a 2.8-meter module length and 1.75-module radius.[16] A full-sized reactor will be likely no larger than a car. The FRC is currently tested with D-T fuel, yet it is forecasted to handle more complex and safer fuels. It will likely run on V-D^{3}He fuel, which will leave smaller radioactive waste than the D-T fuel and, thus, will also be more suitable for nuclear proliferation.[17] There is a high likelihood that FRC would be compatible with p-^{11}B fuel, a third generation fuel that does not produce any harmful waste.[18] With regards to safety, unlike the tokamak, the FRC does not face the risk of thermal quench getting deposited

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[15] Loren Steinhauer, "FRC 2001: A White Paper on FRC Development in the Next Five Years," Advanced Energy Technology Group, U.C. San Diego, 1996. http://www-ferp.ucsd.edu/PUBLIC/AC-PANEL/REC-DOCS/W-PAPERS/frc-2001.html (accessed on August 14, 2007).
[16] J. Santarius et al., "Field-Reserved Configuration Power Plant Critical-Issue" Fusion Technology Institute, University of Wisconsin, 1999. http://icf4.neep.wisc.edu/pdf/fdm1084.pdf.
[17] J. Santarius, G. Kulcinski, and L. El-Guebaly, "A Passively Proliferation-Proof Fusion Power Plant," Fusion Technology Institute, University of Wisconsin, 2002. http://fti.neep.wisc.edu/pdf/fdm1214.pdf.
[18] Samuel Cohen, "A Fusion Power Plant Without Plasma-Material Interactions," Princeton Plasma Physics Lab, 1997. http://www.pppl.gov/pub_report//1997/PPPL-3245.pdf.

inside the core chamber, which could melt some of the metal in the reactor. Thus, the FRC is safer than the already relatively safe tokamak.[19]

Figure 5:
Key Fusion Fuels*

First-generation fuels:

$D + T \rightarrow {}^{4}He\ (3.52) + n(14.07\ MeV)$

$D + D \rightarrow {}^{3}He(.82\ MeV) + n(2.45\ MeV)$ {50%}

$\rightarrow T\ (1.01\ MeV) + p(3.02\ MeV)$ [a] {50%}

Second-generation fuels:

$D + {}^{3}He \rightarrow {}^{4}He(3.67\ MeV) + p(14.68\ MeV)$

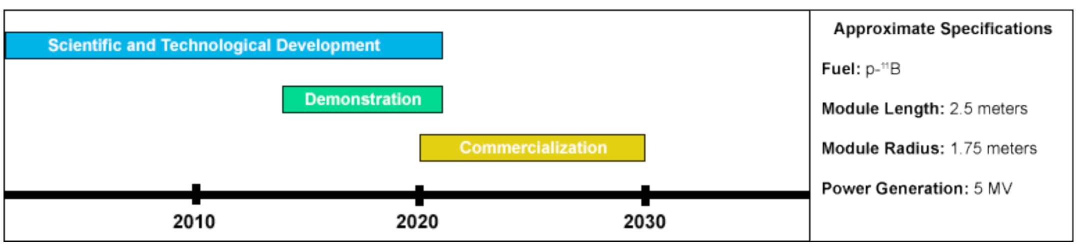
Third-generation fuels:

${}^{3}He + {}^{3}He \rightarrow {}^{4}He(12.86\ MeV) + 2p$

$p + {}^{11}B \rightarrow 3\ {}^{4}He(8.68\ MeV)$

* Source: J. Santarius et al., "A Passively Proliferation Proof Fusion Power Plant"
[a] The produced Tritium can react with Deuterium and cause an "unexpected" D + T reaction.

Figure 6:
Timeline of Development and Approximate Specification for FRC



An optimistic timescale for development of a commercial FRC reactor design is 25 years: 15 years for understanding the physics behind the FRC and creating a Demo and 10 for building a commercially viable reactor.[20] This timescale is much shorter than the one for tokamak and mainstream fusion reactor designs because the small size and cost of FRC reactors allows scientists to build experimental reactors more frequently and, thus, more quickly find an optimal design.

Once developed, the FRC will appear in a very different commercial state than will a conventional fusion reactor design. While a tokamak will likely produce 500 MW or more, an individual FRC reactor is projected to produce about 5 MW.[21] As a result, FRC-based fusion power plants will compose a distributive power grid instead of a central power grid. At this state, there are too many unknown variables about FRC reactors to approximate costs.

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[19] Loren Steinhauer et al., "Modeling of Field-Reversed Configuration Experiment with Large Safety Factor," *Physics of Plasmas* 13.5 (2006).
[20] Samuel Cohen. 2007. Interviewed by Author. Princeton, NJ, July.
[21] Cohen, "Fusion."

Competition and Economic Competitiveness

State of the Energy Market

The total world consumption of energy was 446.7 quadrillion British thermal units (Btus) in 2004. OECD countries consumed 239.8 quadrillion Btus, 32.9 quadrillion Btus more than Non-OECD countries. The United States consumed 100.4 quadrillion Btus. Energy consumption can be categorized into transportation, residential, commercial, and industrial sectors. The transportation sector accounted for about three tenths of energy demand in the United States[22] and a fifth of the energy demand worldwide.[23] With personal automobiles constituting the largest segment of energy consumers in the sector,[24] the transportation sector primarily utilizes petroleum for its energy needs.[25] The residential sector accounts for about a fifth of energy consumption in the United States[26] and a tenth worldwide.[27] Natural gas and electricity are its primary energy sources. The commercial sector accounts for about a fifth of energy consumption in the United States[28] and a tenth worldwide. Lastly, the industrial sector accounts for about a third of energy consumption in United States[29] and over half worldwide. In the industrial sector primarily oil, natural gas, and coal are utilized, whereas in the commercial sector all sources of energy are used.

The Energy Information Administration predicts that in 2030 the world's energy consumption will be 702 quadrillion Btus, almost twice as much as in 2004. Utilizing 403.5 quadrillion Btus, Non-OECD countries will consume more energy than OECD countries, which are projected to consume 298 quadrillion Btus. The transportation sector will have the fastest growth in demand at 0.9% in OECD countries and 2.9% in Non-OECD countries. The commercial sector is expected to overtake the residential sector in energy consumption. The industrial sector will face strong growth in Non-OECD countries at 2.5%. The demand for electricity, currently generated primarily from coal, natural gas, and nuclear fission, will nearly double from 16,424 billion kWh to 30,364 billion kWh. Overall, of all energy sources, natural gas is expected to have the largest increase in use worldwide. However, coal, abundant in China, India, Russia, and the United States, will play an even more important roll in electricity generation than it did in

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[22] Department of Energy, U.S. Energy Information Administration (EIA), "International Energy Outlook 2007", DOE/EIA-0484(2007), May 2007. http://www.eia.doe.gov/oiaf/ieo/index.html.
[23] Robert Q. Riley Enterprises, "Energy Consumption and the Environment" Robert Q. Riley Enterprises. http://www.rqriley.com/energy.htm (accessed August 12, 2007).
[24] Department of Energy, U.S. Energy Information Administration (EIA), "Energy Efficiency – Transportation Sector," EIA. http://www.eia.doe.gov/emeu/efficiency/ee_ch5.htm (accessed August 14, 2007).
[25] Robert Q. Riley Enterprises, "Energy."
[26] Department of Energy, U.S. Energy Information Administration (EIA), "State and U.S. Historical Statistics," EIA. http://www.eia.doe.gov/overview_hd.html (accessed August 14, 2007).
[27] McKinsey Global Institute, "Curbing Global Energy Demand Growth: The Energy Production Opportunity," McKinsey Global Institute, http://www.mckinsey.com/mgi/publications/Curbing_Global_Energy/index.asp (accessed August 12, 2007).
[28] EIA, "Historical."
[29] Ibid.

2004. Electricity from renewable sources is expected to grow at a rate of 1.5% annually, not enough to make renewable sources major players in the market. It is important to notice that the EIA projections assume current laws and policies. They do not account for the potential impact of 2007 Energy Bill[30] or future legislation that may ensure stronger restrictions on carbon emissions or aim to pursue alternate energy paths.[31]

Energy-Related Concerns and Possible Solutions

The two primary energy concerns in the Untied States are energy security and global warming. American energy security worries primarily step from large and growing imports of oil. However, there is also concern that the United States will need to import natural gas in large amounts in the near future, since consumption of natural gas is projected to increase by 50% in the next twenty years and will outpace domestic production.[32] With regards to global warming, the prospects of dramatic changes in global temperature are estimated to require 10% abatement of carbon emissions in the near future and 20% in about a century for optimal economic growth, assuming the possibility of climate thresholds.[33] Unlike solutions for energy security, carbon emissions abatement does not solely depend on domestic actions and policies. In order to maintain low levels of carbon dioxide in the atmosphere, global action is required, especially since Non-OECD countries are projected to pollute more than OECD countries by 2030.[34] This in-itself is problematic because, for many countries, including China, curbing carbon emission at this time will result in high costs on current economic growth that may outweigh benefits of carbon emission reduction.[35]

Solutions for energy security aim to reduce American consumption of oil primarily in the transportation sector, but also in the industrial sector. For the transportation sector, the search for solutions includes development of electric, hybrid, and hydrogen vehicles as well as research of alternative fuels and conservation, as specified by the FreedomCAR & Vehicle Technologies Program.[36] With regards natural gas imports, the goal is to minimize increase in demand for natural gas within all sectors.

The solutions for global warming aim to reduce the expected growth in global carbon emissions. In a famous paper, Professor Pacala and Professor Socolow of Princeton proposed a methodology based on wedges to undercut carbon emissions growth for the next fifty years. Based on the current growth rate, reduction of seven

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[30] Edmund Andrews, "Senate Adopts an Energy Bill Raising Mileage for Cars," *New York Times*, June 22, 2007. http://select.nytimes.com/gst/abstract.html?res=FB0911F73B5B0C718EDDAF0894DF404482.

[31] EIA, "International."

[32] White House. "Reliable, Affordable, and Environmentally Sound Energy for America's Future." Report of the National Energy Policy Development Group, 2001. http://www.whitehouse.gov/energy/

[33] Klaus Keller, Benjamin Bolker, and David Bradford, "Uncertain Climate Thresholds and Economic Optimal Growth," *Journal of Environmental Economics and Management* (August 10, 2001).

[34] EIA, "International."

[35] Samuel Frankhauser and Snorre Kverndokk, "The Global Warming Game – Simulation of C02 Reduction Agreement," *Resource and Energy Economics* 18 (1996), 83-102.

[36] Department of Energy, "FreedomCAR and Vehicle Technologies Program," Energy Efficiency and Renewable Energy. http://www1.eere.energy.gov/vehiclesandfuels/index.html (accessed August 14, 2007).

wedges is needed to ensure that no growth in carbon emissions occurs during this time period. Utilizing current technology, each of the following actions has the ability to remove a wedge:[37]

1. More efficient vehicles
2. Reduction of vehicle use
3. More efficient building
4. More efficient base-load coal power plants
5. Replace coal plants with natural gas plants
6. Capturing CO_2 at base-load of coal plants
7. Converting captured CO_2 to hydrogen
8. Converting captured CO_2 to synfuels
9. More nuclear fission plants
10. More wind power
11. More solar power
12. Producing hydrogen from wind power
13. Biomass fuel fossil fuel
14. Reduction of deforestation, increase reforestation
15. Extension of conservation tillage to all cropland

Considering these methods have to be used in very large scale to have an effect on the amount of carbon dioxide in the atmosphere, pursuing them will be at best difficult. The following are possible challenges to some of methods presented:

- Efficiency, forestation, and conservation tillage – Increases in efficiency, forestation, and conservation tillage will be hard to achieve since they will require people to adopt new lifestyles and industries to invent new energy-efficient technologies and produces in developed and developing countries.[38]

- More nuclear fission plants – While there is more popular and political support for nuclear power plants[39] and an MIT study reported that the plants could be economically competitive if externalities of pollution and rising fossil fuel prices are included in the costs of coal and natural gas power plants,[40] nuclear fission continues to produce radioactive waste and to be a potential cause for nuclear proliferation. Despite newer technology, the risk of accidents is still significant, as shown by the recent radioactive leak in Japan.[41] Furthermore, the necessary dramatic increases in nuclear fission power to combat global warming will likely cause uranium to be a scarce resource,[42] while reprocessing of the fuel will remain expensive[43] and damaging to nuclear nonproliferation efforts.[44] In addition, the increases will lead to substantially great amount of radioactive waste needed to be specially stored.

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[37] Stephen Pacala and Robert Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science* 305(5686), 2004, 968-972.
[38] Ibid.
[39] Peter Baker and Steven Muftov, "Bush Calls for New Nuclear Plants," *Washington Post*, May 25, 2006. http://www.washingtonpost.com/wp-dyn/content/article/2006/05/24/AR2006052402072.html.
[40] John Deutch et al. "The Future Of Nuclear Power", an MIT Interdisciplinary Study, 2003. http://web.mit.edu/nuclearpower.
[41] Associated Press, "Japanese Nuke Plant Leaked After Quake," *CNN*, July 16, 2007. http://www.cnn.com/2007/WORLD/asiapcf/07/16/japan.quake.ap/index.html.
[42] Martin Hoffert et al., "Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet", *Science* 298.1 (2002), 981–986.
[43] John Deutch et al. "Nuclear."
[44] Frank Von Hippel, "No Hurry to Recycle," *Mechanical Engineering* (May 2006), 33-35.

- Increase power from wind and solar – While wind and solar panels are favorable power sources, both are limited in a number of ways: Windmills can only be installed in certain areas with frequent, strong winds. Solar panels have a theoretical 24% efficiency peak for obtaining energy, while most commercial panels are 15% to 20% efficient; thus, in order to generate 10 terra-watts of electricity, enough to become the main global power source, 220,000 square km of solar panels will have to be installed.[45]

- Increase of biomass fuels – Obtaining energy through photosynthesis, biomass naturally has a very low power density. In order for it to significantly effect carbon emissions, about 10% of the Earth's land surface will have to be covered with corn or other crops.[46]

Furthermore, many of the presented methods, directly or indirectly, will lead to an increase in demand for natural gas. One of the obvious paths for cutting down carbon emissions is replacing coal plants with natural gas plants, which are more environmentally friendly, but will cause demand for natural gas to surge. The call for more efficient and less polluting cars will likely cause an increase in demand for natural gas. An MIT study on the prospects of future automobile technology determined that natural gas-based internal combustion engine hybrids would be the least pollutant of the analyzed vehicles, while remaining economically competitive (Figure 7).[47] Supporting this projection, Honda started selling a natural gas car, the Civic GX, [48] in the United States. Another two methods for cutting down emissions – using captured carbon in coal plants and/or energy from windmills to generate hydrogen for vehicles and other modes of transportation - will indirectly lead to a higher demand for natural gas. There are many doubts whether there will ever be a "hydrogen economy" or at least one in the next fifty years, because there are technological problems with transporting, storing, and utilizing hydrogen at economically competitive prices.[49] However, if these challenges are overcome and a hydrogen infrastructure is built, natural gas will become one of the primary sources of hydrogen, since production of hydrogen from natural gas will be the cheapest in the nearer term.[50]

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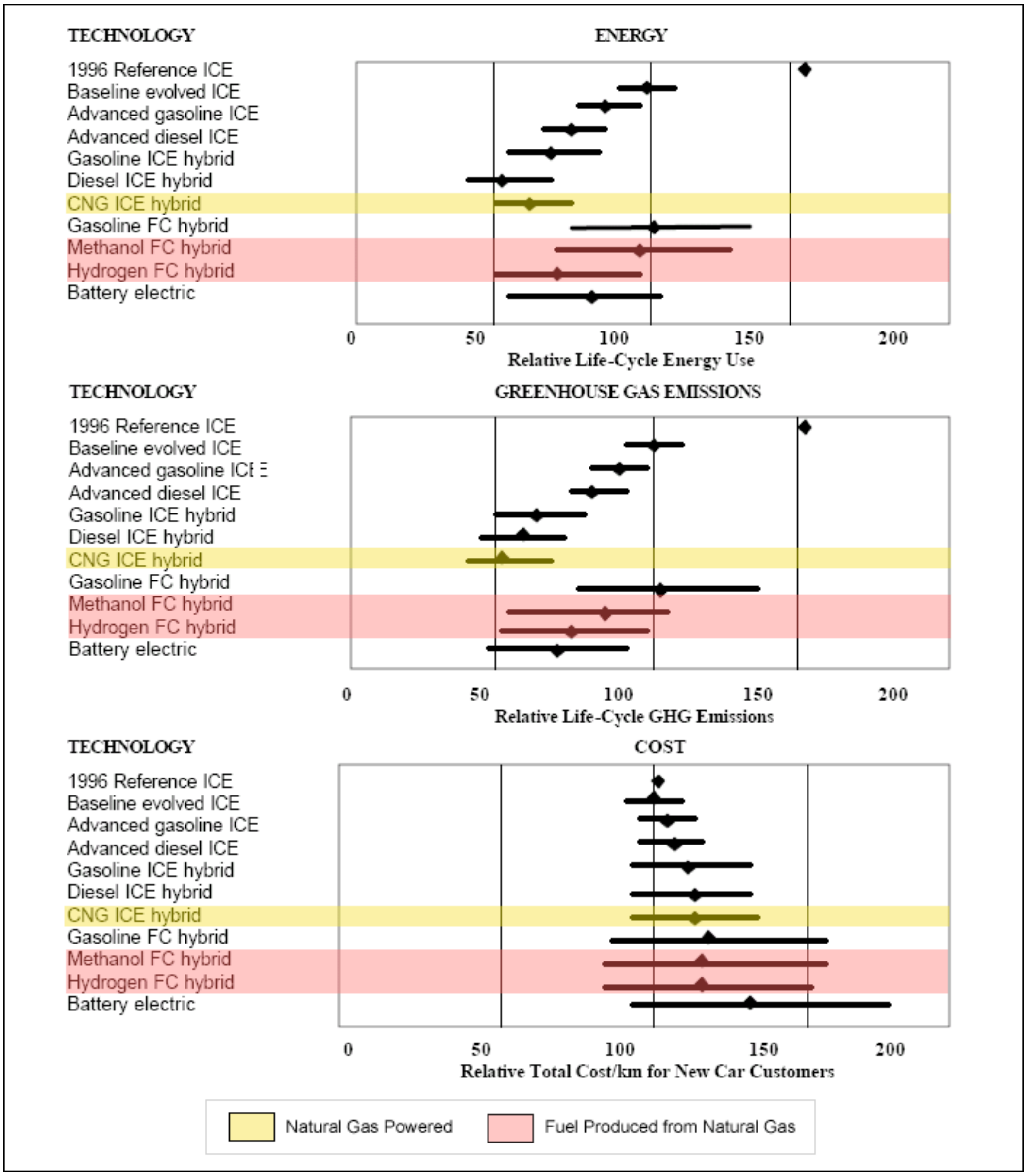
[45] Hoffert, "Technologies."
[46] Ibid.
[47] Michael Weiss et al., *On the Road in 2020,* Energy Laboratory Report # MIT EL 00-003 (Cambridge, MA: Energy Laboratory, Massachusetts Institute of Technology, 2000). http://web.mit.edu/energylab/www/pubs/el00-003.pdf.
[48] Honda, "2007 Honda Civic GX," Honda, http://automobiles.honda.com/civic-gx/ (accessed August 12, 2007).
[49] Robert Service, "The Hydrogen Backlash," *Science* 305 (13 August 2004), 958- 961.
[50] Timothy Lipman, "What Will Power the Hydrogen Economy? Present and Future Sources of Hydrogen Energy," Institute of Transportation Studies, 2004. http://pubs.its.ucdavis.edu/publication_detail.php?id=172.

Figure 7:
Life-Cycle Comparisons of Technologies for 2020 Mid-Sized Passenger Cars*



*Source: Weiss et al., "On the Road in 2020," MIT, 2000.
[a] ICE = Internal Combustion Engine, FC= Fuel Cell
[b] Bars show estimated uncertainty

If natural gas becomes the prominent energy source, as predicted by some energy experts,[51] new global political implications will arise. The United States currently imports 18% of its natural gas; 86% of these imports come from Mexico and Canada. However,

[51] Peter Odell, *Why Carbon Fuels Will Dominate The 21st Century's Global Energy Economy* (Essec, UK: Multi-Science Publishing Co. Ltd., 1998).

based on current laws and policies, the Energy Information Administration projects faster growth in natural gas demand than domestic production.[52] Assuming additional increase in natural gas demand due to carbon dioxide abatement efforts, the United States may need to import large amounts natural gas from abroad in form of liquid-natural-gas (LNG). Overseas transportation will add a substantial markup on the price of natural gas, but more importantly, the United States will be dependent on foreign countries for a primary fuel. The countries the United States will be dependent on will not be the same ones as it does for oil. This change may not be politically favorable.

Correspondingly, some countries will become more important fuel exporters than they are in today's market (Figure 8). Instead of Saudi Arabia, Russia will become the most important player in the natural gas market, because it has 27% of all proven reserves and a competitive geographic edge for selling natural gas to Europe and Asia.[53] While the Middle East has dominance over the oil market with 65% of all proven reserves, [54] Russia, the former Soviet Union states, and Eastern Europe have 35.7% of all proven natural gas reserves.[55] The Middle East had just 36.0% of all proven reserves, with Iran, Qatar, Saudi Arabia, and United Arab Emirates (UAR) having the largest reserves, respectively. However, with exception of Qatar, most of the Middle Eastern countries currently do not have the infrastructure to support mass natural gas exports.[56] Thus, at least in the early in 21st century, Russia will dominate the natural gas market. The country along with other countries that have large natural gas reserves may form an OPEC-like cartel. While there are certain technical difficulties that make a natural gas cartel harder to achieve than an oil cartel, namely the high costs of storing excess natural gas for market flooding, countries with major natural gas reserves have already met in Gas Exporting Countries Forums to discuss the natural gas market.[57]

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[52] White House, "Energy."
[53] http://www.eia.doe.gov/emeu/international/reserves.html - CEDIGAZ
[54] Amy Jeffer and Ronald Soligo, "Market Structure in the New Gas Economy: Is Cartelization Possible?" In *Natural Gas and Geopolitics: From 1970 to 2040* (New York: Cambridge University Press, 2006), 439-464.
[55] Ibid.
[56] Ibid.
[57] Ibid.

Figure 8
Countries with Largest Oil and Natural Gas Proven Reserves

Oil Reserves

Rank	Country	Proven Reserves (billion barrels)
1	Saudi Arabia	264.3
2	Canada	178.8
3	Iran	132.5
4	Iraq	115.0
5	Kuwait	101.5
6	United Arab Emirates	97.8
7	Venezuela	60.0
8	Russia	39.1
9	Libya	35.9
10	Nigeria	35.9

Natural Gas Reserves

Rank	Country	Proven Reserves (trillion cu ft)
1	Russia	1,680
2	Iran	971
3	Qatar	911
4	Saudi Arabia	241
5	United Arab Emirates	214
6	United States	193
7	Nigeria	185
8	Algeria	161
9	Venezuela	151
10	Iraq	112

*Source: Infoplease, "Greatest Oil Reserves by Country, 2006." http://www.infoplease.com/ipa/A0872964.html. Infoplease, "Greatest Natural Gas Reserves by Country, 2006." http://www.infoplease.com/ipa/A0872966.html.

Market Potential for Conventional Fusion Reactors

Estimated to be commercially available between 2050 and 2080, conventional fusion reactors are expected to cost about 8.5% more per COE than nuclear fission reactors (Figure 4).[58] However, nuclear fission COE costs are likely to substantially rise if nuclear fission becomes a more prominent energy source in this century, because more nuclear fission plants will cause greater demand for a finite amount of uranium, leading uranium prices to rise, and will produce more radioactive waste that will need to be managed in more costly ways. Not accounting for these potential price increases, studies estimate that nuclear fission is cost competitive in the United States if a carbon tax is factored into the price of coal and natural gas plants (Figure 9).[59] With regards to these price estimates, nuclear fusion is cost competitive with coal plants and natural gas plants in case of high gas prices. However, at the time when fusion is expected to become economically competitive, there is a high likelihood that greater concerns about global warming associated with more carbon dioxide in the atmosphere and greater demand for natural gas will substantially increase the costs of coal and gas plants. Thus, compared to nuclear fission, natural gas, and coal plants, nuclear fusion will likely be an economically competitive and probably an economically favorable energy source.

[58] Percentage is calculated by average of potential fusion prices compared to average of fission prices.
[59] John Deutch et al. "Nuclear."

Figure 9
Costs of Electric Generation Alternatives (85% capacity factor, 40-Year Life-cycle)*

Base Case	Cents/kWh (no tax)	Cents/kWh ($50/tC)	Cents/kWh ($100/tC)	Cents/kWh ($200/tC)
Nuclear Fusion	~7.8	~7.8	~7.8	~7.8
Nuclear Fission	6.7	6.7	6.7	6.7
Coal	4.2	5.8	7.0	9.4
Gas (low)	3.8	4.5	5.0	6.0
Gas (moderate)	4.1	4.7	5.3	6.4
Gas (high)	5.6	6.0	6.8	7.8
Gas (high) Advanced	5.1	5.5	8.2	7.1

*Source: Deutch et al. "The Future of Nuclear Power." Prices for all alternatives, but fusion, are based on current rates. The prices will likely be different when fusion becomes a commercial alternative.

Conventional fusion reactor's market prospects go beyond solely effecting electricity generation. Fusion plants will be able to produce methanol and hydrogen that, along with electricity, have prospects of becoming predominant energy sources for vehicles. In fact, the MIT *On the Road in 2020* report stated that only fuel cell and electric battery cars have the ability to minimize carbon emissions in the long run.[60] Since fusion reactors will be much safer than fission reactors and will not release carbon dioxide like coal plants, fusion plants could be built closer to urban centers. This may allow excess heat from reactors to be used as for industrial production, water desalinization, and residential heating. [61] However, fusion reactors likely would not fully replace coal, oil, and gas use in industrial settings, because it will not be economically viable for a fusion power plant to solely serve an industrial park and allow the industrial sector the necessary energy source flexibility.

Lastly, conventional fusion plants will have an edge at curbing carbon emissions in foreign countries. While many countries will be reluctant to adopt expensive technologies whose sole purpose would be to curb global warming, many of these countries will enjoy the prestige of having nuclear technology. Thus, they are more likely to invest in nuclear plants than other carbon dioxide abatement methods. For instance, Algeria, Egypt, Morocco, Tunisia, UAE and Saudi Arabia have declared that they are interested in obtaining nuclear plants.[62] However, nuclear proliferation worries prevents developed countries from building nuclear fission plants in developing countries without great cautions and limitations. On the other hand, it is very difficult to build nuclear bombs out of tritium waste. Developed countries, less concerned about nuclear proliferation, will be wiling to export fusion reactors to developing countries eager to

[60] MIT Auto
[61] Satoshi Konishi, "Use of Fusion Energy as a Heat for Various Applications," *Fusion Engineering and Design* 58-59 (2001), 1103-1107.
[62] Richard Beeston, "Six Arab States Join Rush to go Nuclear," *Times Online,* November 4, 2006. http://www.timesonline.co.uk/tol/news/world/middle_east/article624855.ece.

obtain nuclear technologies. Thus, nuclear fusion will be effective in curbing pollution in developing countries.

Market Potential for Unconventional Fusion Reactors

Unlike conventional fusion reactors, each FRC is likely to generate about 5 MW of electricity. Coupled with its small size, very low accident risk, and minimal radioactive waste, the FRC will appear in the energy market in a very different state than conventional nuclear fusion, nuclear fission, or coal power plants. FRC-based power plants will consist of either one or group of FRC reactors. The plants will be located either in population centers or very close to them.

Both the small size and proximity to customers will give FRC-based plants an edge over large power plants. Due to FRC's small size, the investment and the duration of construction for each plant will be relatively small. As a result, each additional FRC plant would be construction only when demand starts to rise. Used near full capacity, an FRC plant will start accumulating returns on investments quickly. On the other hand, large power plants are very expensive to construct and the construction typically takes half to a full decade. Large power plants have to be constructed long before rise of demand, which is typically overestimated. Once built, a portion of the plant's power generation capacity remains unused until "demand grows into it." This rigid adjustment to demand is costly.[63] Furthermore, an FRC-based distributive power grid will more reliable since a failure at one small plant will have substantially less effect on supply than a failure at one large plant.[64]

Not only will FRC-based plants' proximity to customers minimize losses of electricity during transmission, but also allow the plants to serve purposes other than electricity generation. Excess heat from the plants could be used more easily for residential heating, since a stream of hot water from the plants would not have to travel too far to reach households. The FRC-based plants could be located in industrial parks or even in individual factories, providing the industrial sector with a flexible energy source not obtainable from electricity generated at conventional fusion or fission plants. Additionally, FRC-based plants could facilitate the creation of the "hydrogen economy." One of the main technological difficulties of the "hydrogen economy" is transporting hydrogen.[65] However, FRC-base plants could generate hydrogen locally, diminishing the distances hydrogen will have to be transported.

Lastly, FRC-based power plants will be more marketable to developing countries than large low-carbon emitting plants, because FRC-bases plants require small investments. Developing countries would not have to face a decision about investing in a few very expensive power plants, but rather iteratively build small FRC-based plants, gradually shifting into "greener" power generation.

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[63] Amory Lovins, *Small is Profitable: The Hidden Economic Benefits of Making Electric Resources the Right Size* (Snowmass: Rocky Mountain Institute, 2002).
[64] Ibid.
[65] Robert Service, "The Hydrogen Backlash," *Science* 305.5658 (2004), 958-961.

Fusion's Potential Effect on Fossil-Fuel Exporting Countries

Fusion has the potential to replace most natural gas power plants. It also has the potential to either generate electricity or hydrogen that could be used in future battery or hydrogen power vehicles. Thus, fusion along with other technological advances could greatly diminish the demand for oil and natural gas, which would have substantial effects on oil and gas exporting nations, particularly in the Middle East.

The decrease in demand for oil and natural gas may facilitate democratic reform in fossil fuel-exporting economies. A study[66] showed that oil-exporting and mineral-exporting countries are more likely to have autocratic regimes. This correlation has been proven to be statistically significant even when other factors are accounted for (Figure 9). Possible explanations for this phenomenon relate to the fact that oil production and mineral mining are very profitable yet fairly low-labor intensive businesses. Thus, those who control production or mining, which in many countries are governments, become wealthy without richening too many people in the process. The governments may use their wealth to maintain low tax rates and high spending to dampen pressure for democracy or they may build up armies to protect their rule. It is also possible that only small portions of these countries' populations have educated jobs that traditionally lead people to demand democracy.[67] Thus, since exportation of oil and other richening resources for export-based economies is one of the factors impedes democratic reform, a decrease in demand for oil and natural gas, possibly due to the introduction of fusion to the energy market, will remove at least one barrier between these countries and democracy.

Figure 10
Resource Wealth and Democracy[a]
(Dependent Variable is Regime)

Regime	.253*** (.0203)
Oil	-.0346*** (.0051)
Minerals	-.0459*** (.00778)
Income (log)	.922*** (.105)
Islam	-.018*** (.00208)
OECD	1.47*** (.308)
Observations	2183
States	113
Log Likelihood	-3133

* Significant at the .05 level; ** significant at the .01 level;
*** significant at the .001 level
[a] Source: Michael Ross, "Does Oil Hinder Democracy?"

[66] Michael Ross, "Does Oil Hinder Democracy?" *World Politics* 53 (April 2001), 325-361.
[67] Ibid.

Conclusion

Compared to nuclear fission, used today in power plants, nuclear fusion is much safer and will cause few if any problems for nuclear nonproliferation. Utilizing an abundant fuel, it also generates considerably smaller amounts of radioactive waste with a short half-life. There are two paths of development for nuclear fission. The conventional path centers on large reactors, based on such designs as the tokamak. These reactors are going to be comparable in capability to modern day nuclear fission reactors, even though they have additional flexibilities. Because they are very expensive and take very long to construct, at the nominal level of researching funding, a commercial fusion reactor will likely only be available in about 50 to 70 years. The second, unconventional path is based on small reactors called the FRCs. FRCs are safer than the already safe conventional fusion reactors. Expected to generate about 5MV, their small size is particularly advantageous, since it may lend FRC-based plants additional flexibilities. These flexibilities include small initial construction investments, proximity to customers, capability to produce hydrogen locally, and ability to solely serve industrial parks. If rigorous research and development into FRCs takes place, they are likely to be commercially available as early as 25 years from now.

Due to growing concerns about global warming and energy security, the energy market, which fusion reactors aim to enter, is now starting to transform. Many of the proposed ideas and technologies regarding how it could transform, particularly to reduce carbon emissions, directly or indirectly, lead to greater use of natural gas. Not only will natural gas prices rise with higher demand, but also will lead the United States to depend on countries other than Canada and Mexico for the fuel. The countries that will become the largest natural gas exporters will not necessarily be the ones that are now the largest oil exports. Particularly, Russia will become the dominant player in the natural gas market, since it has the largest natural gas reserves and the most developed natural gas infrastructure. This shift may not be favorable to the United States.

In the energy market, both conventional and unconventional fusion reactors are likely to be economically competitive and politically favorable. The COE of conventional fusion energy is estimated to be 8.5% more expensive than the current CEO of nuclear fission. However, cost of managing radioactive waste and price of uranium are likely to increase in the future, making nuclear fission more expensive. When a carbon tax is factored in as well as a likely increase in natural gas prices, nuclear fission and, thus, nuclear fusion become economically competitive with coal and gas power plants. While there are no cost estimates for unconventional fusion reactors yet, the benefits that they will offer due to their relatively small size will give them an edge over alternatives, not only in electricity generation market, but also in sectors in which electricity today is not the primary energy source. Furthermore, both reactors will be more marketable than alternative to developing countries, which are projected to pollute more than developed countries by 2030.

Once a major player in the market, fusion energy in either state could reduce demand for natural gas and, along with advanced in fuel cell and/or electric batteries, for all fossil fuels. Since a correlation exists between oil exports and autocratic regimes, a decrease in demand for fossil fuels would remove one barrier for fossil-fuel exporting countries, such as the ones in the Middle East, from attaining democracy. Thus, the United States would benefit from energy independence, while fossil-fuel exporting countries potentially from democracy.

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